DETERMINATION OF WAVE, SURGE, AND SHIP MOTION

U.S. NAVAL STATION LONG BEACH, CALIFORNIA

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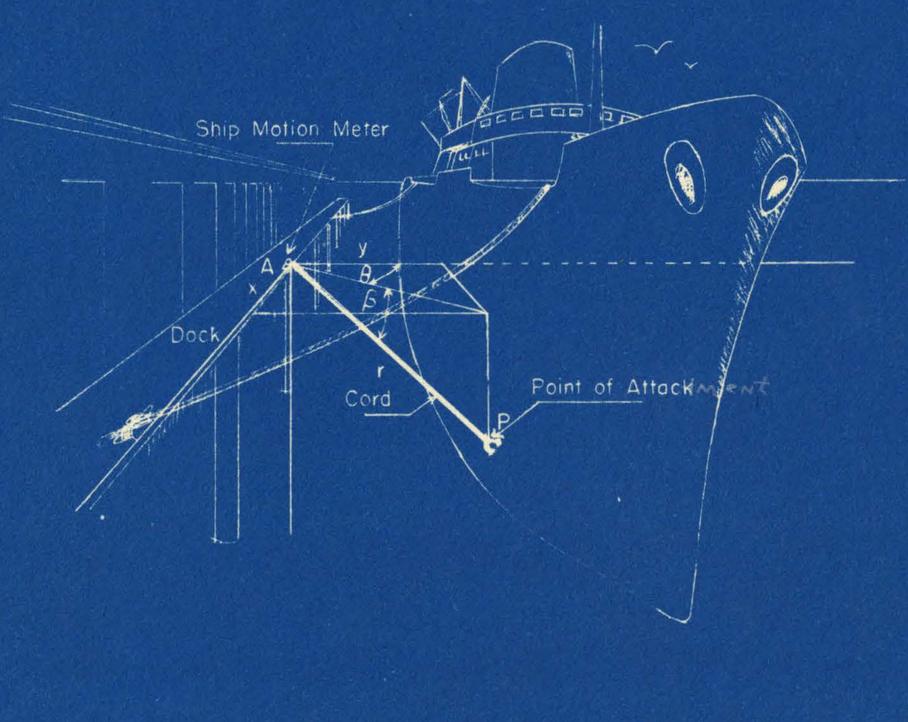

FINAL REPORT OF RESEARCH PROGRAM UNDER CONTRACT NOy-13116
BUREAU OF YARDS AND DOCKS OF THE DEPARTMENT OF THE NAVY

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The Determination of WAVE, SURGE, AND SHIP MOTION at the U.S. Naval Station Long Beach, Calif.

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May, 1951 Pasadena, California Final Report

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ACKNOWLEDGMENTS

This program of instrument development and the subsequent measurement of water and ship motion at the U. S. Naval Station, Long Beach, California, was the outgrowth of recommendations made in the report of the Hydraulic Structures Laboratory of the California Institute of Technology on "Wave and Surge Study of the Naval Operating Base, Terminal Island, California", issued January 1945. These recommendations received the approval of Vice Admiral B. Moreell (Ret.) who was then Chief of the Bureau of Yards and Docks. Without this approval and the interest of Rear Admiral J. J. Manning (Ret.), who succeeded him as Chief of the Bureau, the study would never have been possible. A special word of appreciation is due Rear Admiral J. F. Jelley, who has had direct personal contact with the project during its entire life, first as Deputy Chief of the Bureau under Admiral Manning, and later as Chief of the Bureau. His interest, understanding, and encouragement has been a continuing source of inspiration. Grateful acknowledgment also is made of the cooperation and interest of the chiefs of the Design and Research Sections of the Bureau of Yards and Docks. Two civilian members merit special mention. The late Harris E. Epstein followed closely the technical aspects of the entire program and contributed much to the progress that was made. Nelson M. Brown rendered invaluable assistance, first in helping to develop a type of contract under which it would be possible to carry out the noncommercial research and development program contemplated, and second, in continuing to lend a helping hand during the life of the contract in many matters of procurement, fiscal, and technical details.

The project was fortunate in having as Officer-in-Charge of Construction Captain H. E. Wilson and Captain C. W. Coryell. These officers took a personal interest in the program and did everything in their power to make the work a success. Mr. Frank F. Mead, as the personal representative of the OINCC, rendered invaluable service during the entire life of the program, not only in regard to the administrative details of the contract, but also in technical help and suggestions drawn from his long experience as harbor engineer. All the members of his staff were also extremely cooperative, particularly Mr. D. V. Ratcliffe and the late Mr. G. H. Gideon.

Grateful acknowledgment also is made of the competent and loyal technical staff of the project itself to whom is due the major credit for the results obtained. During the first part of the program, the work was in charge of Mr. Robert E. Carr, who was succeeded by Mr. John T. McGraw. The design and the development of most of the instruments are due largely to the efforts of Mr. McGraw, who also has played a major role in the writing of this final report. Mr. G. R. Chambers also took an important part in the development and measurement program. Others who have been of major assistance in this program include Mr. Haskell Shapiro and Mr. Clarence Edwards on the electrical elements of the instruments, and Mr. Edison Hoge and Miss Margaret Walker on the photographic aspects. My secretary, Grace Newberg, in addition to the countless hours of detail work, is solely responsible for the typing and composition of this final report. Last, but not least, I wish to acknowledge sincerely the continuing cooperation and technical assistance, during the entire program, of my colleague and close associate, Professor Vito A. Vanoni.

I.

DELINEATION OF PROBLEM AND SUMMARY OF ACTIVITIES

Purpose of Study

The wave and surge study, Contract NOy-13116, had as its ultimate objective the evaluation of the acceptable upper limits of water motion for different types of waterfront activities carried on in a modern harbor. Previous experience had made it clear that relatively little work had been done in this field and that few satisfactory instruments or techniques were available for the carrying out of such a program. Therefore, in order to obtain the objective, it seemed necessary first to decide what field measurements were pertinent; next to develop methods and instruments for obtaining the measurements, then to plan and carry out a measurement program, and finally, to analyze and evaluate the data obtained. Since the Los Angeles Harbor was a convenient location for the contractor, and since it is a major harbor with a wide scope of activities, it was chosen as the site for all of the field tests and measurements of the project.

A secondary objective of this study grew out of the fact that a mole had been constructed recently to protect the area of the U. S. Naval Base within this harbor. This construction had been guided by an extensive model study carried out at the California Institute of Technology. It was therefore felt desirable to ascertain, if possible, how nearly the protection afforded by this mole agreed with that predicted on the basis of the model study.

Analysis of Problem and Plan of Attack

Initial study of the problem quickly revealed that if satisfactory quantitative information were to be obtained, it would be necessary to develop a complete battery of instruments for this purpose. It was realized that this was a major undertaking which was certain to occupy the largest part of the time and effort available. This situation was discussed with the representatives of the Bureau of Yards and Docks and it was agreed that the design, construction, and testing of such a battery of instruments would be the chief result to be expected from the contract. It was understood that after the instruments were developed and tested all remaining time within the contract period would be used in making pertinent field measurements.

The problem can be broken down as follows: The purpose of a harbor is to provide conditions under which a great variety of activities can be carried on between floating ships and the land. The great majority of these activities require that there should be little relative motion between the ship and the land. The maximum amount of relative motion that can be tolerated depends upon the type of activity. Thus, passenger ships and light freight can be transferred between ship and shore with little difficulty in spite of quite high relative motion. The transferring of heavy articles of freight can tolerate much less relative motion and the transferring and installation of major pieces of equipment or ship structure demands that if any motion exists it should be of quite small amplitude and long period. The general causes of ship motion are winds, waves, and currents. Steady currents of normal velocities cause little trouble if adequate mooring is provided. Direct wind forces on ships are seldom important. Thus, wave action is the important factor in producing undesirable ship motion and the primary reason for constructing breakwaters and moles is to furnish protected areas in which the wave motion is reduced to tolerable amplitudes. The ship motion is the direct source of difficulty in waterfront operations, but the underlying cause of such motion is the water motion itself.

A little further study of the problem shows that in general the horizontal components of the ship motion are the most troublesome since their amplitudes are considerably greater than the vertical components. On the other hand, waves are generally described in terms of their period and vertical amplitude. However, the horizontal components of the ship motion are obviously linked with the horizontal components of the wave motion. Therefore, it was decided that instruments would be developed to measure these horizontal components of ship and water motion.

Previous experience had demonstrated that these motions varied a great deal with time so that to be representative, measurements would have to be made over a relatively long period of time, i.e., periods measured in weeks rather than in hours. To meet this requirement, it was decided that all of the instruments should be of the recording type and that the recorder itself should be capable of making a continuous record over a relatively long period of time.

Review of Instrument Development

The Ship Motion Recorder was one of the first instruments developed. When attached to a berthed ship by means of a light cord, this machine is capable of making a continuous record of the horizontal motion of the center of gravity of the ship. The periods and amplitudes of the motion of the ship can be determined directly from this record. Further developments have made it possible to incorporate additional units to measure roll and yaw. Thus, all of these motions may now be recorded simultaneously. It is felt that this instrument is a very important tool for the measurement of harbor performance as it makes it possible to obtain quantitative measurements to replace estimates and opinions.

The vertical motion of the ship is not recorded directly by the Ship Motion Recorder. Instead, it was felt that it would be more satisfactory to obtain a direct measurement of the vertical motion of the water surface. The normal wave or tide recorder was not considered suitable for this purpose. In the first place, it was felt desirable to have all the information recorded simultaneously on the same chart. In the second place, it was desired to eliminate the surface chop which does not produce ship motion. The Bottom Pressure Recorder was developed to meet this need.

The companion instrument to the Ship Motion Recorder is the Current Meter. This instrument has as its objective the continuous measuring and recording of the magnitude and direction of the horizontal water motion. The first model was designed to operate when installed on a submarine structure, such as a pile. The reason for using such an installation for the first model was primarily that if the current meter is to record the direction of the motion, the orientation of the meter itself must be known at all times. This is accomplished if the meter is fastened in a known position to a permanent fixed structure. However, preliminary tests of the operating conditions show that the use of the machine was hampered badly by the difficulty of making a satisfactory underwater installation on available marine structures. Hence, to make the Current Meter readily portable and easily installed, the Current Meter Levelling Tripod was designed and constructed. As the name indicates, this provides a three-point mounting for the Current Meter. After the Tripod and Meter are installed on the bottom, the meter can be levelled by remote control from the surface. Furthermore, the tripod also contains a compass and indicating transmitter. This makes it possible to determine the orientation of the Current Meter as soon as it is installed and this orientation can be checked at any time thereafter.

In order to obtain a simultaneous record of all of the information furnished by the complete Ship Motion Meter, the Bottom Pressure Meter and the Current Meter, a special 35 mm Recorder was designed and constructed. This unit is fundamentally similar to a multi-channel oscillograph. It differs chiefly in that the film speed is very slow. In fact, a standard 100-ft reel of 35 mm microfile film is sufficient for a continuous record over a period of three weeks.

One other development program for making special measurements was undertaken. One of the secondary objectives of the study was the determination of whether or not the long period surges that were known to be present in the Los Angeles Harbor area exist at the same time in the open ocean outside of the harbor. This required the determination of the absolute values of very small water motions at distances of from one to several miles offshore, i.e., from the nearest fixed reference points. The vertical amplitudes of the surge motion in question range from .1 or .2 ft. up, but seldom reach a foot. This was considered so small as to be impossible of measurement. However, the corresponding horizontal water motion was calculated to be of the order of tens of feet. It was found that a good radar had the required accuracy of measurement. Therefore, an SCR-584 set was obtained and modified for this purpose. Special floats were developed and constructed to carry the radar reflector. The underwater construction was designed to insure that the float would follow the water motion, with little error due to wind forces for any moderate wind intensity.

With this equipment definite evidence of the existence of surge outside of the harbor was obtained. These measurements were not made at the maximum effective range of the radar, but the boat circling tests, similar to those whose records are shown in Fig. 31, demonstrated that surges of moderate intensity would be detectable with this equipment at ranges up to between five and ten miles.

Routine Measurements

In addition to the radar measurements and the records from the special instruments, routine records were obtained from the wave and tide recorders installed in various locations within the harbor. In addition, as part of this project, a mechanical wave recorder was installed at Santa Catalina Island which is about 30 miles west of Los Angeles Harbor. Continuous records were obtained for about two years at this location. These records showed conclusively that the long duration surges which had been observed in the Los Angeles Harbor area and detected by the radar in the open ocean also occurred during the same periods at Catalina Island. Records obtained subsequently from other stations up and down the coast in the Southern California area all confirmed the fact that the long period surges are present in the entire area and do not originate in the harbor and are not confined to it.

ABSTRACT OF RESULTS AND RECOMMENDATIONS

Instrument Development

A number of instruments have been developed for the special purpose of measuring the physical characteristics of harbor performance. The most important instruments in this development program and their respective uses are as follows:

(a) Ship Motion Recorder

This meter measures amplitude and period of various components of motion of berthed or anchored ships.

(b) Bottom Pressure Recorder

This meter measures amplitude and duration of pressure variations on the bottom due to surface waves; hence, in shallow water it measures vertical amplitude and period of these waves.

(c) Current Meter

This meter measures direction and velocity of horizontal water movement at the bottom or at any desired depth of installation below the surface. This instrument is designed particularly to record the oscillating horizontal water movement caused by shallow water waves.

(d) 35 mm Recorder

This instrument is basically a compact oscillograph or recording galvanometer and serves to give a continuous record of the measurements being made by meters (a), (b) and (c). It operates with a special slow motion drive which makes it possible to obtain a three-week continuous record on a 100-ft spool of microfilm.

These four instruments have all been completed, and they have had both shop and field tests. Reliable results can be obtained with them by competent, well-trained instrument technicians.

A technique was developed to measure oscillating current motions in the open ocean. This involved the use of a standard SCR-584 radar set, which was especially modified for the purpose, as well as the development of special floats.

Results from Field Measurements

Field measurements of harbor characteristics were made continuously during the life of the contract. The first measurements were made with existing standard commercial instruments. As each special instrument or technique was developed and tested, it was incorporated and used in the field measurement program. Some of the most important results obtained are as follows:

(a) Records of long period waves or surges have been obtained simultaneously at several coastal stations in Southern California. This indicates that the surge or seiche observed occasionally in the Los Angeles Harbor area is not a local phenomenon, but is merely a manifestation of a general disturbance. These long period waves enter the harbor through the gates, around the open end of the breakwater, and at least in part, through the porous sections of the breakwater itself.

(b) At certain times ships berthed at various locations in the harbor were found to have appreciable horizontal motion. The records show that the periods of these motions were from one to three minutes and the horizontal ship motion was always accompanied by vertical water movement of the same period.

(c) The normal wind waves of 12-to 20-sec. period which enter the harbor through the breakwater gates produce no appreciable horizontal ship motion within the mole and other protected areas within the harbor.

(d) During the rather extended duration of measurements, no high amplitude water or ship motions of any period were observed in the mole, although such motions were known to have occurred during this interval in the outer harbor. This indicates that the mole affords effective protection from the existing surge motion, as well as from the wind and storm waves.

(e) Records of the water motion in the outer harbor confirmed the previous impression that long period surge motion of potentially damaging amplitude is fairly rare in the whole harbor area.

Recommendations

Under this contract major progress has been made toward the ultimate objectives of evaluating permissible water motion in working areas of harbors and in determining the specific characteristics of the Los Angeles Harbor area. The problem has been analyzed and broken down into its component parts and a program formulated. Existing instruments have been evaluated and techniques have been developed for utilizing them for this special purpose within their field prescribed by their individual limitations. Special instruments have been designed, constructed, and proven through field testing for making the necessary measurements that could not be made by the existing commercial instruments. However, there has not been sufficient time available within the contract period to carry on more than a short preliminary series of measurements using the entire synchronized battery of instruments to evaluate the relationship between horizontal water oscillations of various amplitudes and periods and the corresponding motion of ships of various sizes and types. Furthermore, it has not been possible to make any determination of the maximum amount of ship motion that is permissible during the carrying on of the different types of activities in the harbor. These are the next important steps which must be taken in the delineation of the information necessary for the rational design of waterfront structures. An additional factor, which is also of great importance and is closely allied to these two, is the determination of the force exerted by a ship in oscillatory motion upon its moorings, either through tension in the cables or by direct contact between the ship and the structure.

It is recommended that these three factors: (a) the relation between horizontal water motion due to waves and induced ship motion, (b) the maximum allowable ship motions for different classes of harbor operation, and (c) the forces exerted by ships in oscillatory motion on their moorings, be made the subject of additional quantitative study at the earliest possible opportunity.

III.

INSTRUMENTS DEVELOPED FOR THIS STUDY

Basic Principles, Methods of Construction, and Techniques of Operation

A. Ship Motion Recorder

Purpose. - The Ship Motion Recorder was designed for the special purpose of recording the motion of berthed or moored ships. The study of wave and surge in Los Angeles Harbor necessitated the physical measurement of the frequencies and amplitudes of moored ships so that their response to various wave excitations could be evaluated quantitatively.

Development. - During the period 1943-45 attempts were made to obtain field measurements of oscillatory motion of ships moored to the outfitting piers at Terminal Island. These measure-were badly needed for the purpose of supplying information to guide the model study which was then under way in the Hydrodynamics Laboratories of the California Institute of Technology. The objective of this study was the determination of the best design of the mole for the protection of the Naval Base.

Two measuring techniques for the determination of ship motion were tried. In the first measurement a numbered measuring grid was attached to the ship side. This was observed through a transit in a fixed position on the pier and a record was made of the motion of the grid as a function of time. The second method substituted a motion picture camera for the transit. Pictures of the ship and grid were made from the fixed location on the pier. The camera was operated at a relatively low number of frames per second. Both methods proved to be very time-consuming. The transit method required two technicians constantly during the time the measurements were made. Even so it proved impossible to take points at short enough time intervals to give a smooth plot of the ship motion versus time. The camera method required the constant presence of only one operator and produced enough points to make a continuous smooth plot, but it required an additional large amount of time in the office to measure each picture and plot the resulting data.

Both systems showed the same critical defects. Periods of the wave and surge activity of high enough intensity to cause serious ship motion occurred at relatively rare intervals and at unpredictable times. This meant that operators had to be stationed at the ship 24 hours a day even though several days or even weeks might elapse without the occurrence of any significant ship motion. It proved infeasible to maintain such a watch even under the emergency conditions existing at the time the mole was being designed and constructed. The result was that records were obtained only for a very few moderate surge periods and no measurements were secured of some of the most intense surges because they occurred during the night or over the week-end when no observers were available to make records.

This experience showed conclusively that the only satisfactory method of obtaining the records of ship motion necessary for the carrying out of a systematic study of the type contemplated under this contract was through the use of an instrument which incorporated a continuous recording system. Since no such instrument was available or had yet been developed, it was decided to design and construct one for this specific purpose.

Design of Ship Motion Recording Unit. - Of the six components of motion of a ship, those of horizontal translation of the center of gravity and angular motion about the vertical centroidal axis (yawing) are considered of most immediate concern, since these motions cause the damage to piers and ships. Also, it had been observed that these motions were of the largest amplitude. Vertical translation of the center of gravity of the ship (heaving) had been established as being almost identical with the long period vertical motion of the sea surface and hence could be recorded most conveniently with a simple wave recorder.

Angular motions of the ship about the longitudinal and horizontal transverse axis (rolling and pitching) were worthy of notice, but were not of equal importance with the three motions mentioned above. These three components which were to be concentrated upon will be called in this report "headway", "leeway", and "yaw", and by these terms are meant, respectively, horizontal longitudinal translation of the center of gravity, horizontal transverse translation of the center of gravity, and angular motion about the vertical centroidal axis.

Since the recording device was to be in operation 24 hours per day for a period of several weeks or months, it was evident that, as a practical matter, the device must not interfere with the working of the moored ship nor be susceptible to accidental damage by the crew or equipment of the ship. Also the device would have to be simple and inoffensive-looking, and its use should not require any appreciable alteration or addition to the ship. It appeared that ideally the instrument should be located on the pier and have no physical connection to the ship. A study of possible optical or electronic devices to accomplish this was made, but while some of these ideas appeared promising, they all seemed to have undesirable complexities. In the design finally adopted, the recording instrument was located on the pier and was connected to the ship simply by a 1/16-in. diam. cord under **5**-lb. tension.

The scheme of the instrument is shown in Fig. 1. The cord from the instrument is attached to the ship at point "P", which is on or close to the waterline and on the midship section. The motion of point "P" is continuously transmitted to the instrument by the cord and is there resolved mechanically into its horizontal and vertical components. Point "P" is not the center of gravity of the ship. Therefore, the yawing of the ship causes "P" to move horizontally without reference to the leeway or headway (translation in the horizontal plane). This spurious motion constitutes a source of error in the recordings.

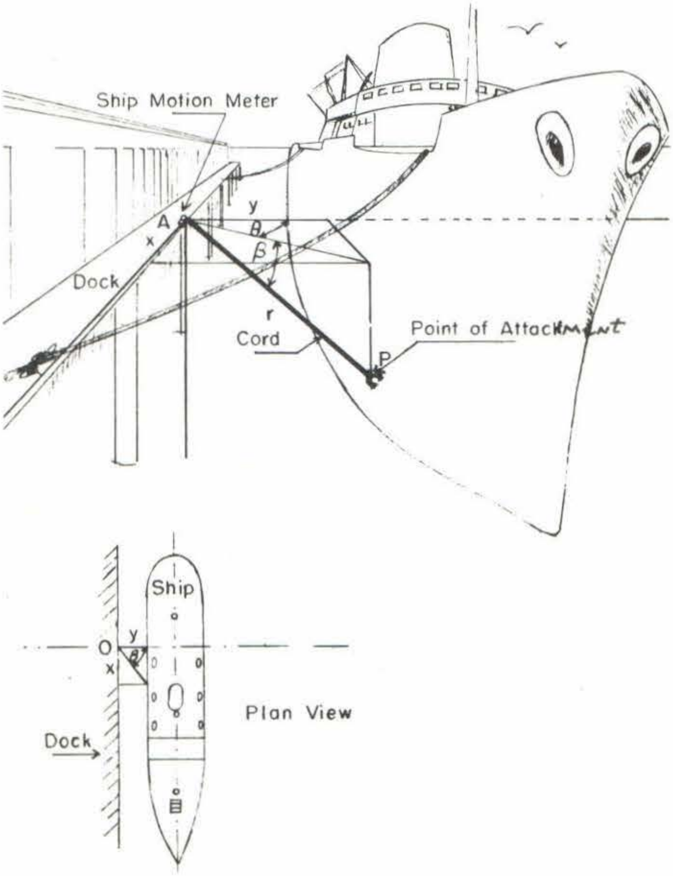


Fig. 1 - Scheme of recording instrument

An investigation of the magnitude of the error due to the fact that point "P" is located on the skin of the ship instead of at the center of gravity, indicated that such errors were relatively small as far as measurements of headway, leeway, and yaw were concerned.

The instrument records the headway and leeway of the ship from the motion of point "P" by a simple cascading of four potentiometers in the following manner:

$$x = r \cos\beta \sin\theta \tag{1}$$

$$y = r \cos\beta \cos\theta \tag{2}$$

where x = headway
y = leeway
r = cord length from P to A
β = vertical angle of r (elevation)
θ = horizontal angle of r with y axis (azimuth)

Eqs. (1) and (2) show that the headway and leeway are both functions of the variables r, β, and θ. These are, in turn, determined by the cord connecting the ship to the instrument. As previously indicated, it is possible to resolve mechanically the motion of the cord in terms of these variables. The four potentiometers are so arranged in the instrument that the moving contact of each potentiometer is positioned by one and only one of the variables to be measured. Thus, one potentiometer arm is actuated by r so that the output voltage is proportional to r, one potentiometer is actuated by β so that its

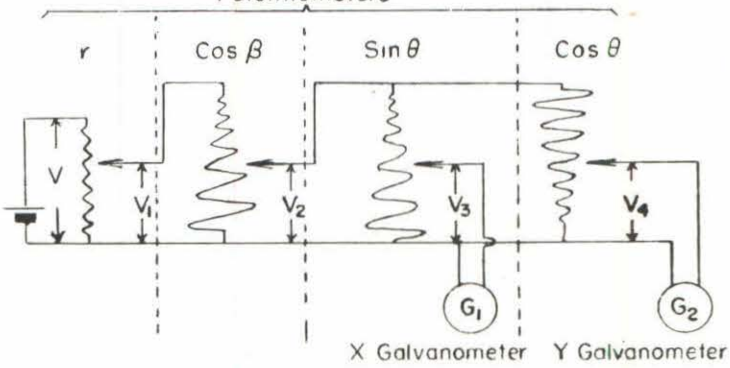
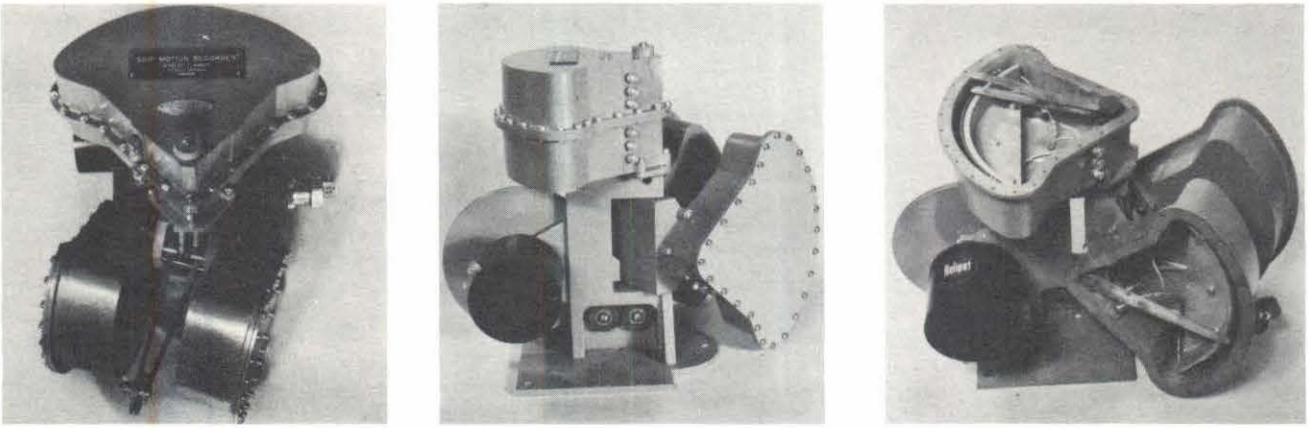


Fig. 2 - Potentiometer circuit diagram

output voltage is proportional to cos β, and two potentiometers are actuated by θ so that one output is proportional to sin θ, and the other output is proportional to cos θ. These potentiometers are then connected electrically, as shown in Fig. 2. It is seen from the consideration of elementary circuit theory that the output voltage, V_3, will be proportional to the headway, x, and V_4 to the leeway, y. If these output voltages are impressed on two elements of a recording galvanometer or oscillograph, records of headway and leeway versus time will be obtained.

meter used to measure the length of cord is a 25 ohm Helipot with 0.5 per cent accuracy. The potentiometers are oil-immersed to give corrosion protection, and the contacting metal is "Paliney No. 7", which is especially suitable for this purpose. 1/

The operation of the instrument is as follows: the motion of the ship causes the counterweighted cord to move in and out and to deflect the follower arm up and down and back and forth. The motion of the cord in and out rotates the 6-in.



(a) Front view (b) Side view (c) Cover plates removed

Fig. 3 - Ship motion meter

A photograph of the Ship Motion Recording Unit is shown in Fig. 3. The main frame and and potentiometer housings are of anodized cast aluminum, shafts are of stainless steel, bearings are grease-sealed, and shaft seals are neoprene O-rings. The cord to the ship is counterweighted with five to ten pounds. This provides sufficient tension to give a satisfactory Helipot drive with a 300 deg. wrap. It also insures that there will be sufficient tension in the cord so that the forces due to the bearing contactor friction and the weight of the follower arm will not be large enough to deflect the cord materially from its true position. It will be seen in Fig. 3 that the arms of the potentiometers used to measure α and θ move linearly with changes in these angles. The sin and cos functions are introduced in the winding of the potentiometers themselves, i.e., they are wound on sin and cos cards rather than on rectangular ones. These cards were designed to give an output accurate to within 1 per cent over 70 deg. range when loaded with 1000 ohms. The sinusoidal potentiometers used on fire control radar sets are accurate to within 0.1 per cent, but none could be found suitable for our purpose, and manufacture of custom potentiometers to such accuracy is prohibitively expensive. The linear potentiometer sheave which positions the contactor of the linear potentiometer (Helipot). This potentiometer has an angular range of 15 turns which corresponds to 23.5 feet of cord. The voltage output of the Helipot is proportional to the length of cord between the ship and the instrument. The motion of the follower arm positions the contactors of the elevation and azimuth potentiometers such that output voltages proportional to cosβ, cosθ, and sinθ are provided. The cascading of these potentiometers results in final output voltages proportional to x and y as explained above. These output voltages are recorded on an oscillograph with a very slow time scale, which permits a three weeks' record to be taken on a 100-ft roll of film. The complete circuit for the unit is shown in Fig. 4. The sensitivity of the system or ratio between displacement of the record and the displacement of the ship can be varied by changing the input voltage of the power supply.

To measure roll a pendulum-operated device has been developed. Its appearance may be seen

[1]Review of Scientific Instruments. October 1946. p. 360.

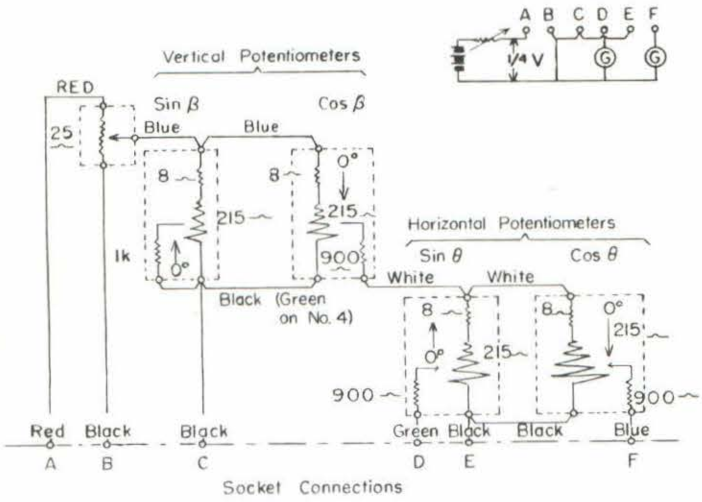


Fig. 4 - Circuit diagram of ship motion meter

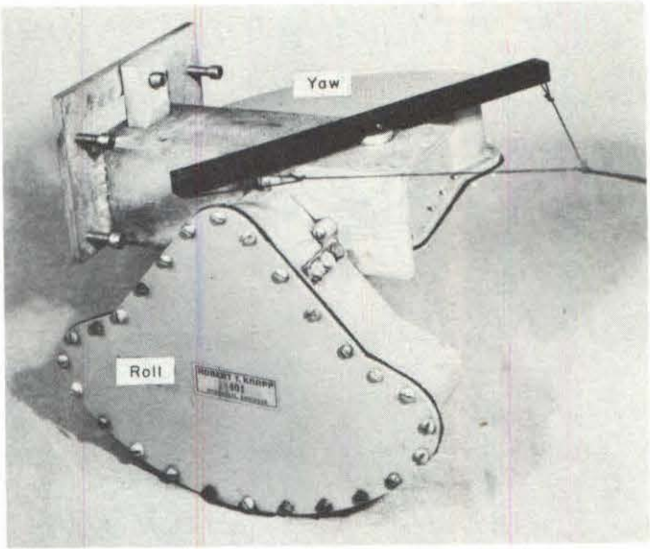
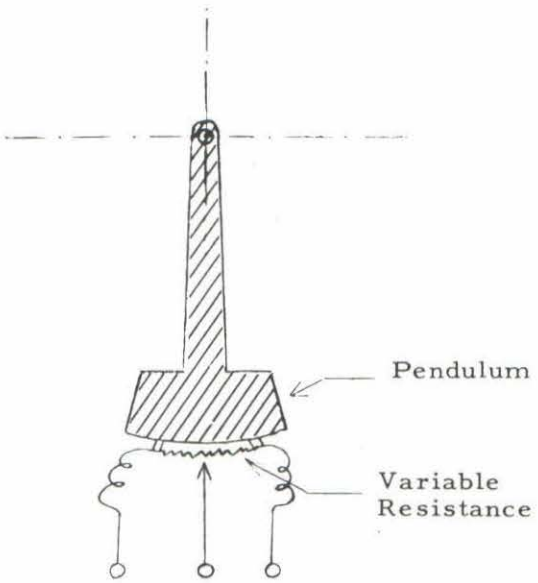


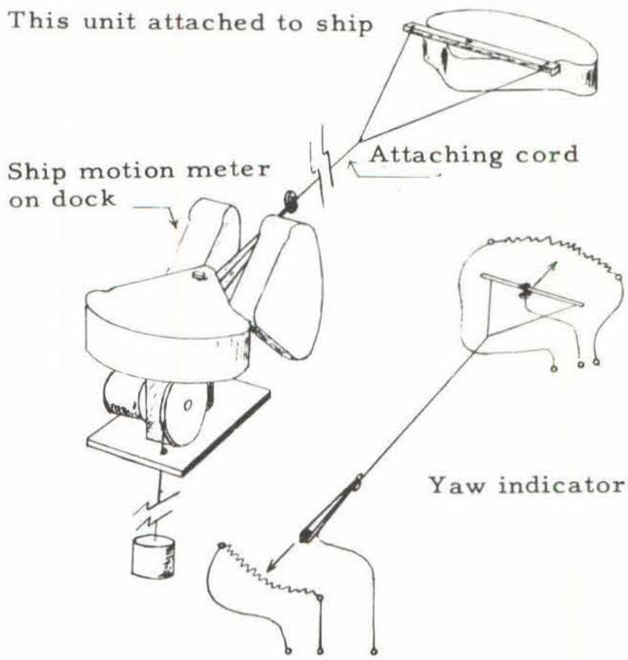
Fig. 5 - Roll and yaw indicator

in Fig. 5 and the scheme of operation in Fig. 6(a). This device is attached to the shipside. When the ship rolls the position of a weighted pendulum changes the resistance of a potentiometer and the change in resistance vs. time is recorded by another galvanometer element of the oscillograph.

Yaw measurement is accomplished by means of the instruments illustrated in Fig. 5 and 6(b). Two potentiometers are provided, one attached to the ship and the second mounted on the vertical spindle of the Ship Motion Meter. The resistance of the potentiometer on the ship is determined by the horizontal angle between the cable and the ship. The resistance of the potentiometer mounted on the vertical spindle is determined by the horizontal angle between the cable and the dock. A simple electrical circuit gives an output voltage proportional to the difference between the two angles. It can be shown



(a) Roll indicator



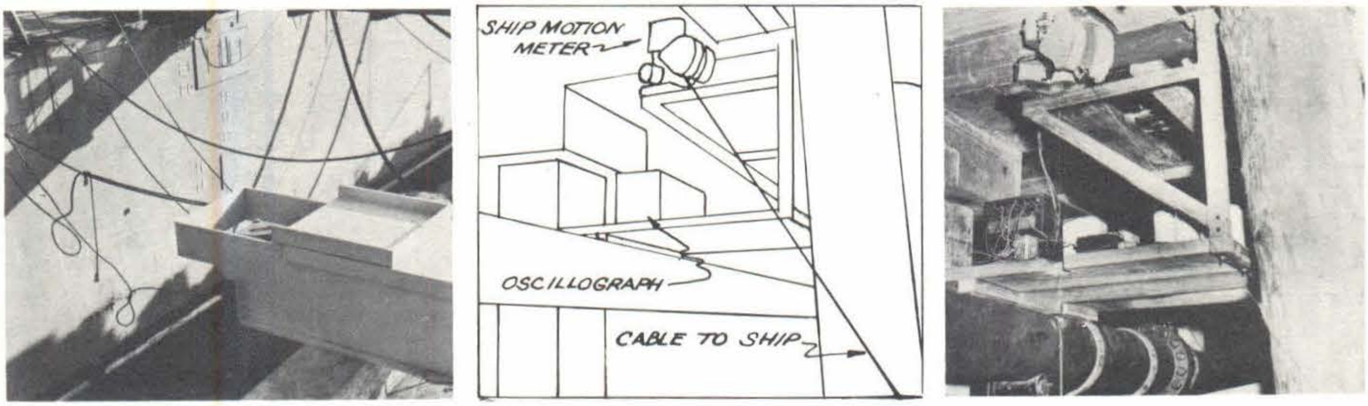
(b) Yaw indicator

Fig. 6 - Schematic diagrams of roll and yaw indicator

that this difference is proportional to the yaw of the ship. Therefore, when this voltage is impressed on a fourth galvanometer of the oscillograph, a record of yaw vs. time will be obtained simultaneously with the other three components of motion. Headway and leeway, unaccompanied by yaw, will give no reading, since the difference between the two angles measured by the yaw potentiometers will remain constant.

Installation and Operation

Two typical installations of the Ship Motion Meter are shown in Fig. 7. The first installation was made on top of the dock as shown in (a). Subsequently, to protect the equipment and eliminate interference with loading and unloading, the instrument and oscillograph were mounted under the dock, as seen in (b). In recent installations the cable has been attached to the ship by using an Alnico permanent magnet. Power requirements are 110 AC for the oscillograph and 1 1/2 volts DC for the Ship Motion Meter. After the device is connected to the ship the only services required are changing the film at three-week intervals and renewing the 1 1/2 volt battery.



(a) Topside installation

(b) Installation under dock

Fig. 7 - Ship Motion Meter Installation

B. Bottom Pressure Recorder

Purpose

The Bottom Pressure Recorder was designed with two purposes in mind. The first was to give an indication of the vertical motion of a ship. The second was to measure wave height and period at any desired location.

Development

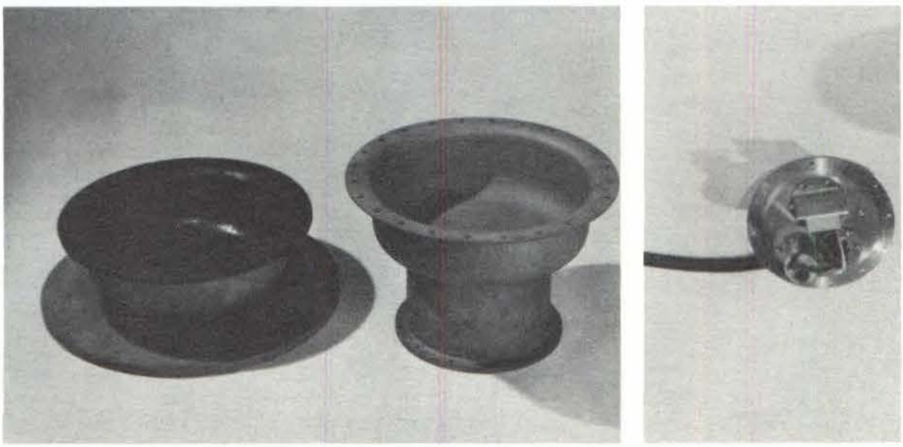
The Ship Motion Recorder measures the modes of motion of the ship that are most important for the study of harbor characteristics. However, it does not measure the vertical motion of the ship. It could be made to do so, although it is somewhat difficult. This difficulty is caused by the fact that the actuating cord is attached to the ship on the outside of the hull instead of at the center of gravity. Thus, most of the vertical motion at the point of attachment is due to roll rather than to actual vertical motion of the entire ship. It would be necessary to remove this large roll component before the true vertical motion could be obtained. However, it is to be expected that the vertical motion of the ship will correspond very closely with the long period vertical motion of the water. This was confirmed by field observation. Therefore, it was decided that instead of trying to measure the vertical motion of the ship directly, it would be quite satisfactory to measure and record the bottom pressure variations due to the passage of the long waves. Such a recorder would not be sensitive to the surface chop which, in turn, does not affect the vertical motion of the ship. It was also recognized that such an instrument would be equally valuable for use in locations in which the primary objective was simply to measure wave height and period at a given location.

The fact that the Bottom Pressure Recorder was intended to be used as an element of a battery of instruments imposed additional requirements. Thus, it was necessary for the device to be readily portable. It was also necessary for it to produce an electrical signal suitable for recording by the same oscillograph that recorded the components of the ship motion. For simplicity, it was also desirable that the electrical requirements of such an instrument should be compatible with those of the other members of the instrument battery.

The first devices considered were those using portable pressure tubes and float wells, but these were discarded because of the relatively cumbersome installation required. It was decided to design a portable bottom pressure chamber which would measure fluctuations due to the changes in the vertical water height and would transmit the results to the surface through a waterproof cable. As an additional design criterion, it was decided that the instrument must be able to record the tide cycle to insure the accurate measurement of all long period waves. The design studies soon showed that a pressure element which was sensitive enough to meet the requirements of the study would be damaged if it were subjected to the pressure change caused by lowering it from the surface to the bottom. Therefore, the instrument was designed with a pressure-equalizing chamber which eliminated the pressure difference on the measuring elements while the equalizing chamber was open during the time the instrument was being raised or lowered. When the instrument was installed on the bottom, communication with the equalizing chamber was cut off by closing the pressure-equalizing valve. This maintained a constant pressure in the reference chamber equal to the average bottom pressure and allowed the pressure element to operate on the difference in pressure between that of the reference chamber and the fluctuating water pressure caused by the passage of waves or change of tide. Considerable difficulty was encountered in the construction of the original instrument due to porous castings. This was obviated in the later instruments by resorting to the use of rolled and spun material which was fabricated by brazing. A photograph of the final model is shown in Fig. 8. A schematic diagram is shown in Fig. 9.

The housing is fabricated out of copper to inhibit the growth of marine organisms. It consists of two separate chambers. The reference pressure chamber is formed of a copper cylinder with an O-ring sealed copper cover plate. The lower chamber, or bellows cage, is fabricated from spun copper surfaces of revolution, and includes a molded neoprene rubber equalizing diaphragm. An external pressure-sensitive bellows is connected to a Statham electrical strain gage located in the reference-pressure chamber. The pressure-equalizing valve is located in the reference-pressure chamber. It seals the reference-chamber from the bellows cage air-chamber except when its operating solenoid is energized. A hermetically-sealed cable terminus enters the reference chamber and connects the equipment to the control box through 100 feet of waterproof neoprene cable. A control box is provided which controls the opening and closing of the solenoid equalizer valve from the surface. Fig. 10 shows the wiring diagram of the Bottom Pressure Recorder and the control box. It will be seen from this figure and the above description that the passage of a wave will change the pressure on the pres-

(a) Recorder Assembled



(b) Recorder Disassembled

Fig. 8 - Bottom pressure recorder

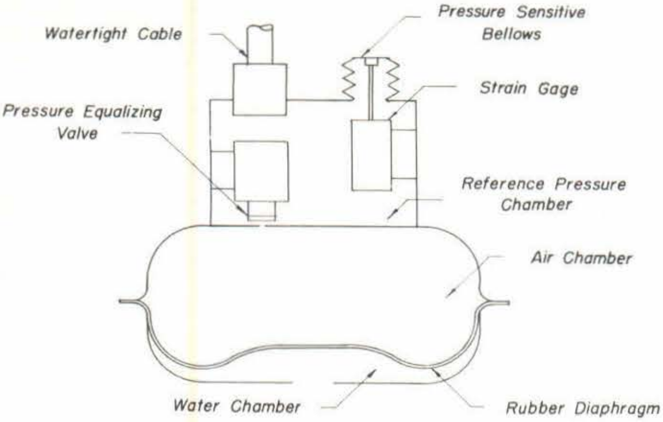
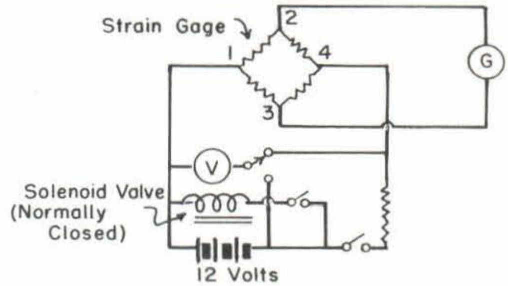


Fig. 9 - Schematic diagram of Bottom Pressure Recorder



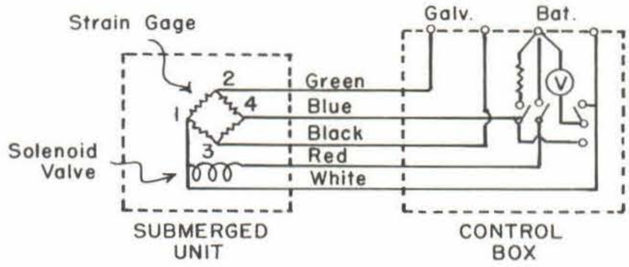


Fig. 10 - Wiring diagram of Bottom Pressure Recorder

sure-sensitive bellows. The bellows, in turn, produce a corresponding change in the force acting on the Statham strain gage. Since the electrical output of this gage is directly proportional to the force acting on it, the signal that goes from the gage to the surface will vary linearly with the height of the wave.

Operation

The instrument is prepared for operation by first pressurizing it with air to 5 lbs/sq. in. and submerging it in water to test for any possible leaks. After satisfactory tests, the pressure is removed and the instrument is ready for operation. To place it in operation, the instrument is connected to the control box, the strain gage switch turned off, and 24 volts DC is applied to the pressure-equalizing valve-actuating solenoid. The instrument is now lowered to the bottom. As it is lowered, the open equalizing valve and diaphragm will maintain the internal pressure equalized with the outside pressure. When the instrument is in place on the bottom, the solenoid equalizing valve is closed. The 24-volt power supply is replaced by a 12-volt power supply. The strain gage terminals are connected to the recording oscillograph and the switch is turned on. The pressure element will then record any changes in bottom pressure due to waves or tide.

It will be noted that there is no basic limitation as to the depth of water in which the instrument will operate successfully, since the instrument case is required to stand only the differential pressure equivalent to the maximum wave height at the surface. For a given design of instrument, however, the maximum depth of operation is determined by the ratio of the volume of the equalizing air chamber to that of the reference pressure chamber. The maximum depth of installation in feet is roughly equal to 33 times the ratio of these two volumes. In the present instrument this volume ratio is approximately 3 1/2. Therefore, the maximum working depth is about 115. To modify the instrument to operate at greater depth, it would be necessary only to increase this ratio by increasing the volume of the equalizing air chamber. Of course, it would be possible to increase the ratio by decreasing the volume of the reference pressure chamber, but this is not desirable since this volume should be very large compared to the volume change produced by the deflection of the pressure-measuring element over its full range.

It will be noted that the service required of the pressure equalizing valve is not very severe. When it is closed the maximum preference differential across it is only that due to the maximum wave height. Small leaks should not produce a cumulative effect since the pressure cycle is oscillating. For satisfactory operation it is necessary only that the leakage volume during one wave cycle be small compared to the volume change required to change the pressure in the reference chamber by an appreciable fraction of the pressure change caused by the passage of a wave.

C. Current Meter

Purpose

The Current Meter is a device designed primarily for measuring the magnitude, period, and direction of horizontal water motion. Two types of horizontal water motion are known to exist: (1) steady currents, and (2) oscillatory motion due to the passage of waves and tides. For the general purposes of this project, it was necessary that the meter be able to measure and record both types of motion.

History and Development

Many ideas were considered for obtaining measurements of these three characteristics of the motion. Some of these were discarded for purely analytical reasons, and some of the more promising ones only after preliminary experiments showed them to be unsuitable. Most of the obvious methods required rotating parts outside of the current meter case. For example a rotating propeller was considered for measuring the current velocity. Also, a wind vane type direction indicator was proposed. Both of these elements required a rotating shaft. Any sort of rotating part outside the meter was deemed inadvisable because the nature of the measurements required that the instrument be capable of operating unattended while submerged in salt water for weeks at a time. Due to the very low velocity currents which it was proposed to measure, the bearings involved in such a machine would have to have extremely low friction, and this was difficult to achieve in a bearing immersed in salt water. Furthermore, this instrument was to be used in a battery of other instruments which required that the measurements be transmitted to a central recorder by electrical means. This meant that the instrument case had to be absolutely watertight since salt water leaks obviously would damage any electrically operated measuring and transmitting elements. A rotating shaft would therefore require an absolutely tight water seal. This, added to the requirement of little or no friction on the shaft, was considered an insurmountable problem. It was finally decided to attempt to measure the current velocity by measuring the force produced by that velocity acting on a drag element attached to the instrument. Such a drag element could be made to indicate both the force and the direction or azimuth of the force. It was decided to use a restrained pendulum for the drag element. The ball of this pendulum could be mounted on a shaft that would pass into the case through a thin rubber seal. This seal could be made leak-proof by securing it solidly both to the shaft and to the case, since no shaft rotation would be required. For such an instrument two separate systems of measuring elements would be required to be mounted in the case: one which would measure the magnitude of the force regardless of the direction from which it came, and the other which would measure the direction of the force unaffected by its magnitude. A further requirement was that the meter should be able to operate at any desired depth and that its electrical requirements and signal outputs should be compatible with the power supply and recording system necessary for the operation of the other instruments in the battery.

Description and Operation

A diagrammatic sketch of the component parts of the current meter embodying these principles is shown in Fig. 11. The case and force pendulum is constructed of copper to inhibit corrosion and marine growth. The entire case is completely filled with a high grade, light, insulating oil. A small rubber bellows is installed as part of the case to equalize the pressure between the oil and the surrounding water. Since the entire case is completely filled with oil, this rubber bellows is required only to be flexible enough to permit the small volume change due to temperature changes and to the compression of the oil as the instrument is lowered from the surface to the bottom. It will be seen that the instrument is similar to the Bottom Pressure Recorder in that its operation is unaffected by depth. In fact, since the Current Meter has no air chamber, one design is suitable for all possible depths of installation. The pressure is equalized at all times so that the case is not even required to withstand the small differential pressures due to the passage of wave trains on the surface. During many weeks of operation in salt water the internal elements of this meter have remained in excellent condition.

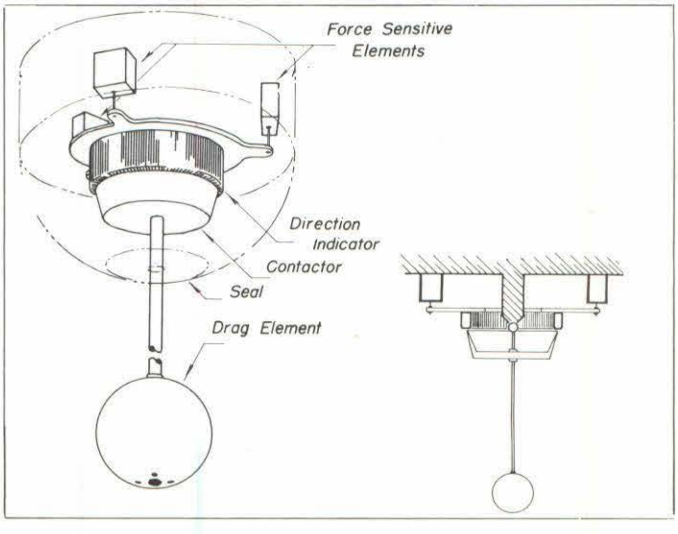


Fig. 11 - Diagrammatic sketch of component parts of current meter

The force of the current on the drag element is measured by the use of Statham strain gages. The Statham strain gage is unlike the bonded wire strain gage in that the wire undergoing strain is not attached to the deflecting element by means of bonding plastics or glue. The force is transmitted directly to the gage and to the sensitive wires through a small threaded shaft. This results in an element which gives trouble-free readings. With a given constant feed voltage this gage will deliver an output voltage which is directly proportional to the applied force. As will be seen in Fig. 11, the drag pendulum is pivoted about a point inside of the case. It is constrained from rotating about the shaft axis, but is free to rotate about either of the two axes which pass through the pivot point perpendicular to the shaft. A three-armed yoke or spider which lies in a plane perpendicular to the pendulum shaft, is attached to that shaft through the direction-measuring device which will be described later. Essentially, however, the spider and direction-measuring device are a rigid part of the shaft and are free to rotate with it. This entire assembly is attached to the case by three of the Statham strain gages previously described, one being fastened to each of the equally spaced (120^{o}) arms of the spider. Thus it is seen that the strain gages supply the only constraint to the rotation of the pendulum and attached yoke. Thus the force of the current on the drag pendulum acts directly on the strain gage. The electrical outputs of the three strain gages are connected in series so that the total output will be the sum of the three individual outputs. This total output, therefore, is directly proportional to the force of the ocean current on the drag element. Since it is necessary to measure very low velocity currents, and hence very small forces, it is also necessary to employ very sensitive, and hence delicate, strain gages. Therefore, it was found essential to develop a means of locking the drag pendulum and the measuring elements in a fixed position while the meter is being transported or installed in order to prevent damage to the measuring elements. A simple, hand-operated, mechanical lock was first used, but this was later replaced by an electrically operated mechanical lock which proved to be far more effective and much easier to use.

The direction-measuring element, which forms the connection between the yoke and the shaft of the drag pendulum, is constructed as follows: A precision cylindrical wire-wound potentiometer is attached directly to the yoke with its axis concentric with the pendulum shaft. A special wind is so arranged that it gives a linear change in voltage from 0 to 360 deg. A sharp-edged frustrum of a metal cone is attached rigidly to the pendulum shaft and adjusted so that there is a very small positive clearance between the sharp edge and the bare windings on the edge of the potentiometer cylinder. This arrangement is also shown schematically in Fig. 10 and it will be observed that the diameter of the edge of the cone is the same as the mean diameter of the potentiometer cylinder.

To visualize the operation of the measuring elements, suppose that the current meter is installed on the bottom and that a water current exists which exerts a force on the sphere of the drag element. This pendulum will swing freely on its cardon-hinge pivot through a very small arc until the sharp edge of the cone on the pendulum shaft makes contact with the active edge of the wire-wound cylindrical potentiometer (the direction indicator). The potentiometer voltage at this point of contact will give a unique indication of the direction of the ocean current. The force caused by the current is transmitted from the pendulum shaft through this contact to the potentiometer cylinder, and thence directly to the spider. Further rotation of the assembly is prevented by the constraint offered by the strain gages. It will be seen, as previously stated, that the strain gages transmit to the case the entire moment applied to the pendulum by the water current. Consequently, the sum of their electrical outputs is directly proportional to the square of the current velocity. This electrical measure of the current velocity is transmitted to the surface through the electrical cable to the recording oscillograph. The direction indicator likewise transmits its output (the voltage at the point of contact of the cone and the potentiometer) to the surface through the same cable to the same recorder. Since the potentiometer is a linearly-wound resistor, this voltage output is directly proportional to the angle between the point of contact and the end of the winding, and hence gives a linear indication of the relative direction of the ocean currents. To obtain the absolute direction of the current, it is obviously necessary to know the orientation of the meter as it is installed on the harbor bottom.

Fig. 12 shows the appearance of the meter as it was installed in the calibrating flume. Fig. 13 is a photograph of the internal mechanism of the meter showing the direction indicator, the spider, and the three Statham strain gages. Fig. 14 is a wiring diagram of the current meter, its control box, and the connections to the recording galvanometer. The lock mechanism used during transportation and installation consists of an electrical solenoid and plunger, together with a mechanical follow-up screw. The plunger, or armature, of the solenoid has a cone-shaped recess which fits over the upper end of the drag element rod and holds it firmly in place. Then the mechanical follow-up screw is turned down by hand to hold the plunger in its down position. The electrical circuit may then be disconnected without disengaging the lock, and the instrument can be transported freely without danger of damage.

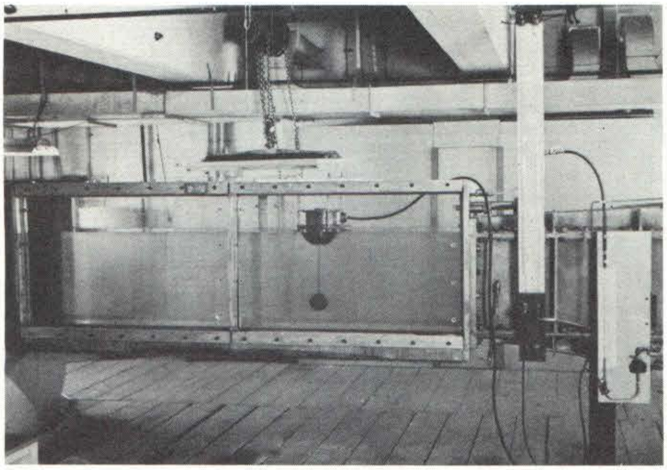


Fig. 12 - Current meter installed in calibrating flume

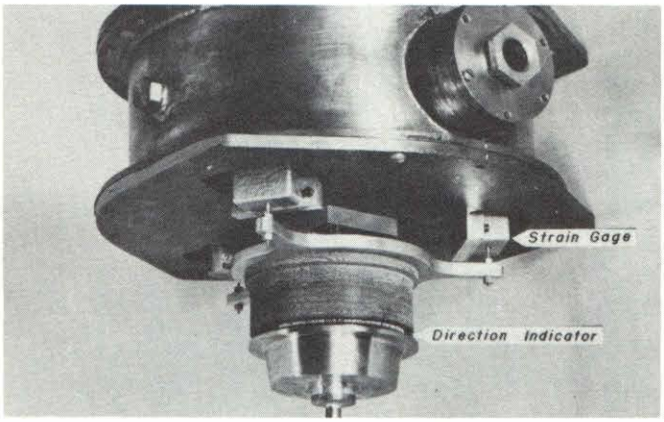


Fig. 13 - Internal mechanism of current meter

Conversely, by using the electrical lock alone, it is possible to lower the whole current meter to the bottom with the drag element and rod securely locked. Then when it is in the desired position, the lock circuit can be opened, thus freeing the pendulum and putting the instrument in operation. The reverse procedure can be used for bringing the current meter to the surface. The mechanical follow-up screw is, of course, used only to conserve the electrical supply as when it is necessary to transport the current meter any great distance, at which time it might be impractical to keep batteries in the circuit. Fig. 15 is a view of the current meter from above. The electro-mechanical lock is in the cylinder projecting from the top. Fig. 16 shows the current meter control box with the cover removed. Fig. 17 shows a diagram of the method used for installing the current meter from a platform just above the water surface and a photograph of the actual installation. Fig. 18 gives a sample record obtained at this installation.

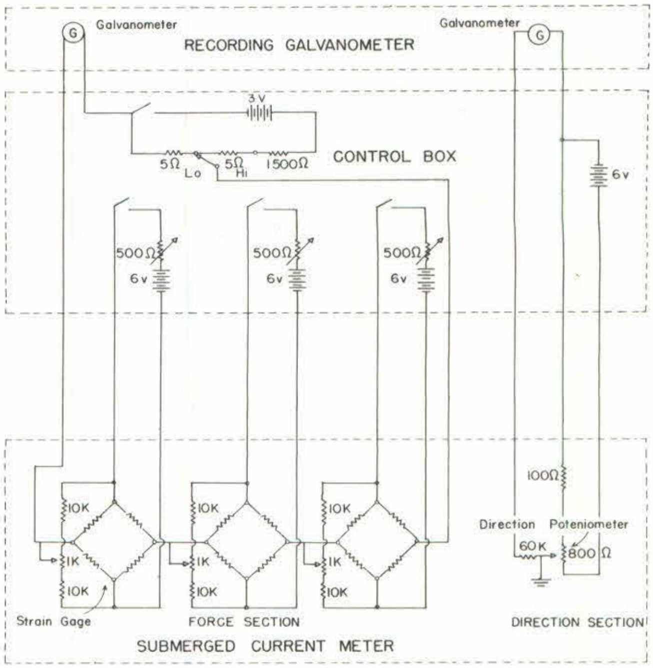


Fig. 14 - Current meter wiring diagram

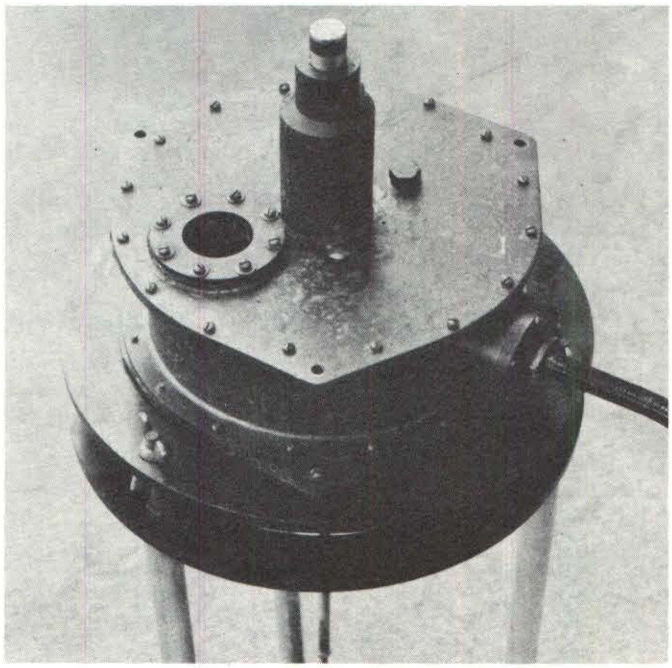


Fig. 15 - Current meter, showing lock

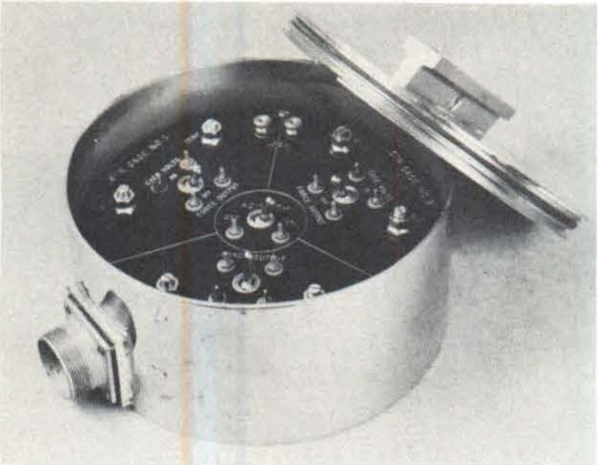


Fig. 16 - Current meter control box

D. Current Meter Leveling Tripod

Purpose

The Current Meter Leveling Tripod is an auxiliary device for the Current Meter to permit it to be supported on the bottom of the harbor or ocean in any desired location without the necessity of having any submarine structure upon which to fasten it. It also furnishes a directional reference, thus making it possible to measure absolute current directions.

History and Development

In order to understand the requirements for a supporting tripod for the Current Meter, it is necessary to consider the purpose and mechanism of operation of the Current Meter itself. The Current Meter is capable of measuring the magnitude, period, and direction of the hori-

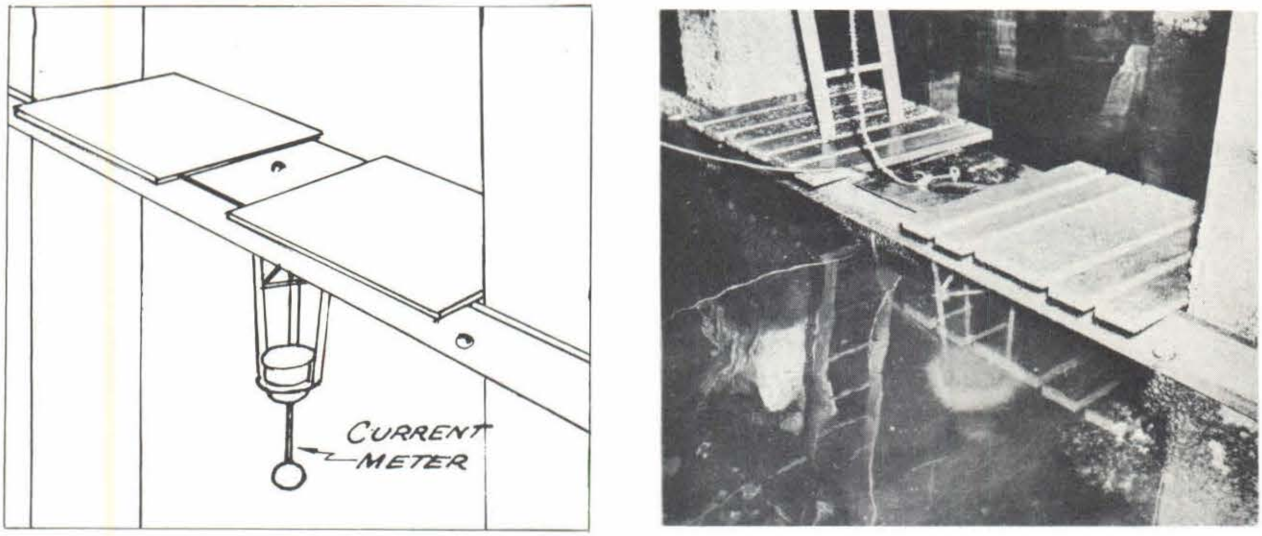


Fig. 17 - Current meter installation

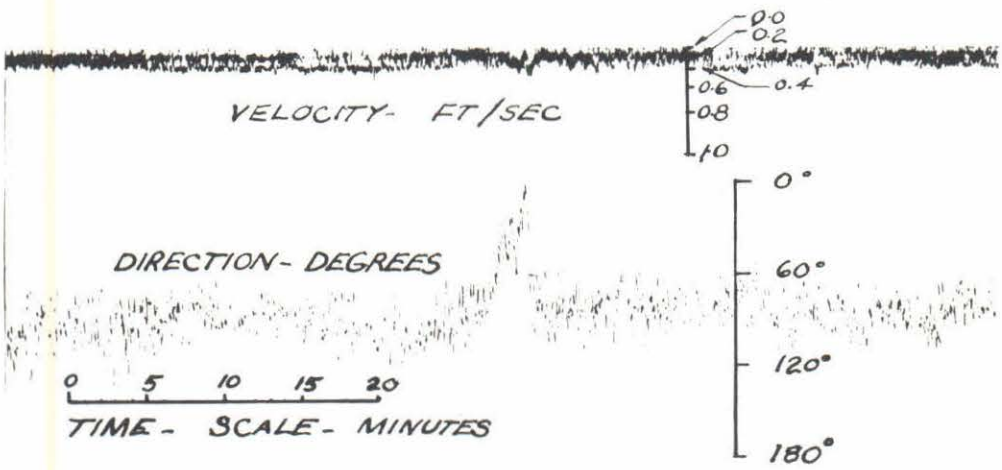


Fig. 18 - Sample record obtained by current meter

zontal water motion. The magnitude is determined by one set of force measurements. The direction is determined by recording the direction from which the force acts on the instrument. The period is a derived measurement from the time record of the force. In principle, the force is measured by a very stiff spring balance. Therefore, it is necessary that the instrument be held rigidly in space and kept relatively level. Since one of the primary requirements of the instrument was that it should be able to measure oscillatory currents, it was imperative that the instrument remained fixed in space. This eliminated the possibility of suspending the instrument from a cable attached to a float or to a fixed structure since in either case the cable would permit the entire instrument to swing as a pendulum with the oscillating water current. The need for measuring the direction of the current imposed an even more rigorous limitation on the supporting system as, in order to give the direction reading any significance, it was necessary that the orientation of the current meter case be fixed and known. The simplest type of mounting that met all of these requirements was a bracket by means of which the Current Meter could be attached at any desired depth to a system of piling.

Current Meter Leveling Tripod

The first tests of the Current Meter were made in this manner with the Current Meter attached to the supporting piles of a pier immediately adjacent to a ship mooring. This was a convenient arrangement for the purpose of making a study of the correlation between the water motion and the ship motion since the Ship Motion Meter and the Bottom Pressure Recorder could also be installed in the immediate neighborhood and the entire battery of measurements could be recorded on the same instrument. However, the actual underwater installation of the Current Meter was found to be rather unsatisfactory. A supporting platform had to be fabricated and installed. Furthermore, the piling obstructed the flow of the current which it was desired to measure. Finally, the next objective of the program was to be able to measure oscillating currents in various locations in the harbor at which there were no permanent structures that could be used for the mounting of the Current Meter. Therefore, to increase the usefulness and versatility of this instrument, it was decided to construct a supporting tripod which could be placed at any desired location on the harbor bottom. This would simplify the installation problem since the gear could be handled directly from a boat. The Recorder could then be installed either on a boat anchored at the Current Meter or on any suitable marine structure within the immediate vicinity.

The requirements for such a tripod are:

1. It must be light enough and small enough to be handled from a relatively small boat.

2. It must be large enough to support the Current Meter far enough off the bottom to keep it out of the mud and miscellaneous debris.

3. It must be rigid and heavy enough to maintain its position without movement in the fastest current that it is desired to measure.

4. After the tripod is set firmly on the bottom, it must be possible to level the Current Meter itself. This leveling must be done to a relatively high degree of accuracy.

5. When the meter is installed, leveled, and ready to be put into operation, it must be possible to determine its orientation with respect to the compass bearing, and it must also be possible to check this orientation at any desired time without disturbing the operation of the meter. It will be seen from these specifications that the tripod cannot be a simple structural support. Instead, it must be a relatively complicated operating machine.

Description

The unit as it was finally constructed to meet these five requirements is seen in the photograph of Fig. 19 and the diagrammatic sketch of Fig. 20. It consists of a structural supporting tripod, a leveling mechanism, and a transmitting compass. Two hundred feet of waterproof multiconductor cable connects the instrument to a remote control box and the necessary auxiliary equipment.

The entire tripod unit is, as far as possible, fabricated from brass. This minimizes corrosion on the external surfaces, and also largely eliminates disturbances to the transmitting compass. The tripod itself is of brass tubing. Hanging inside of this tripod is a brass frame, which is designed as a mounting for the Current Meter itself. It is arranged so that the meter is fastened rigidly below the frame. On top of the frame and fastened rigidly to it are three cylindrical brass containers. Their axes are vertical when the frame is leveled and they are so located that they form an equilateral triangle. The ends are closed and have watertight O-ring seals. The third cylinder houses a transmitting compass and a level indicator. This entire assembly is hung from the main tripod by a three-point suspension which consists of one fixed pivot point (universal joint type), and the two screw rods of the screw jacks. This mounting system permits only two degrees of freedom:

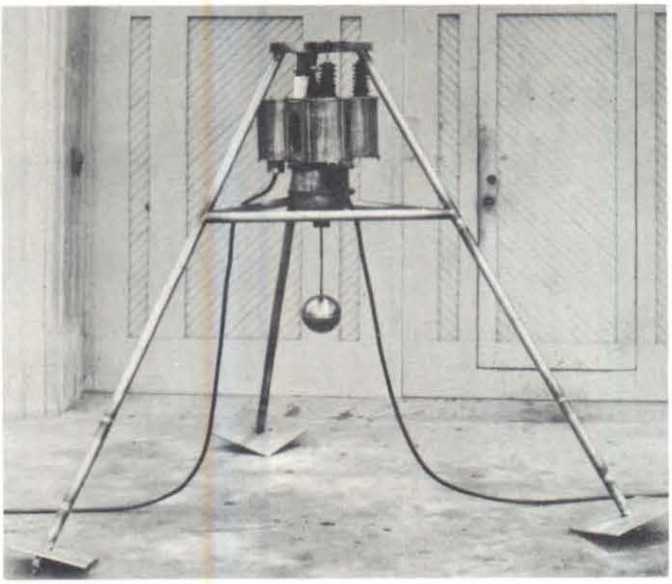


Fig. 19 - Current meter leveling tripod

motion in rotation about two axes each of which passes through the universal joint and one of the screws of the jacks. The universal joint is so located with respect to the two screw jacks that these axes are at right angles. This permits the jacks to be used very conveniently to level the frame since the leveling action of the jacks are independent of each other, ie, they produce motions at horizontal angles which are at right angles to each other. The motion of the screws is sufficient to permit compensating for a 15 deg. slope of the ocean bottom.

All three cylinders on the leveling frame are interconnected with tubing which serves the dual purpose of carrying all of the electrical wiring and of maintaining pressure equalization. A rubber pressure equalizing diaphragm is provided in the compass housing cylinder. After all of the equipment is installed, the entire unit is filled with oil. With this arrangement, internal pressure in the unit always equals the external water pressure, and therefore no pres-

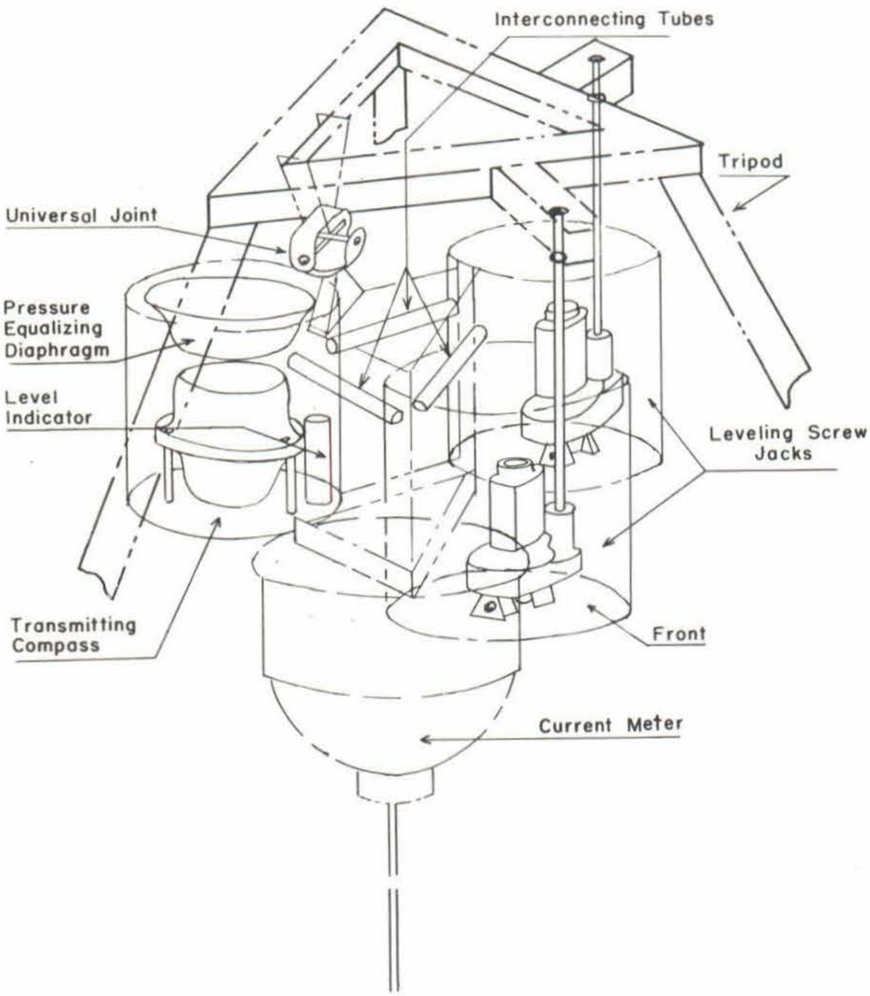


Fig. 20 - Diagrammatic sketch of leveling tripod operating mechanism

sure exists at any time. Since there is no air chamber either in this system or in the Current Meter, there is no limit to the depth at which this combined instrument can be operated. The transmitting compass is a standard aircraft type instrument (completely filled with liquid). The level indicator, which is installed in the same housing, is essentially a simple pendulum which is restrained from movement in the horizontal directions by four screws at right angles, each of which carries an electrical contact. Small clearances are provided between the pendulum and the contacts. These clearances can be adjusted to obtain any desired degree of level sensitivity. Each of these four contacts control an indicating light located in the remote control box at the surface. The remote control box also includes controlling switches for the leveling jacks, the compass repeater, and the power supplies.

Operation

The tripod unit with the Current Meter mounted in place, is wired and tested for satisfactory operation in the Laboratory. The current meter action is then locked, as described in the chapter on that instrument. It is, of course, understood that the meter itself will be maintained in a locked condition until the tripod has been installed on the bottom and leveled. The tripod unit is handled from a boat by means of an A-frame and lowered to the bottom at the point at which measurements are desired. Next a 36-volt, direct current power source is connected to the remote control box and the unit is ready function. In general, two of the leveling indicator lights will be on. By proper manipulation of the screw jack control switches, as guided by the indicating lights, the frame may be leveled. The screws are self-locking, and once leveled, the unit needs no further attention. Next the compass transmitter is energized and the orientation of the entire unit is determined and recorded. All is then ready for putting the Current Meter into operation. Both the level and the orientation may be checked in any subsequent time by simply energizing the level indicator and the compass transmitter. When it becomes desirable to move the unit to a new location it is necessary only to lock the Current Meter before the tripod is hoisted from the bottom. The tripod mechanism itself requires no preparation for hoisting. Fig. 21 shows the remote control box. Fig. 22 contains some views of the tripod and Current Meter during installation at a measuring station in the harbor. Figure 23 is a wiring diagram of the tripod mechanism.

E. 35 mm. Recording Galvanometer

Purpose

The instruments developed under Contract NOy-13116 to measure ship and water action, produce electrical signals proportional to the phenomena measured. The 35 mm. Recording Galvanometer was developed to record simultaneously the signals from the various indicating instruments in a convenient form for data analysis.

Development

The first step in the entire development program was the design and construction of instruments for measuring ship motion and bottom pressure. The indications from these instruments were first recorded on a standard multiple-galvanometer oscillograph, slightly modified to meet the needs of this program. This instrument had nine galvanometer elements which produced simultaneous traces on a roll of 6-in. wide photographic paper. The modification consisted primarily in reducing drastically the speed of the drive for the recording paper and of reducing the intensity of the illumination for the galvanometer mirrors in the correct proportion to get a satisfactory exposure for the individual traces. Although this instrument served satisfactorily during the initial stages, it was not felt to be useful for continuous service in the field. In the first place, it was bulky and produced bulky records. In the second place, it was not designed for continuous output over long periods of time without attendance. In the third place, the instrument was a laboratory instrument, and

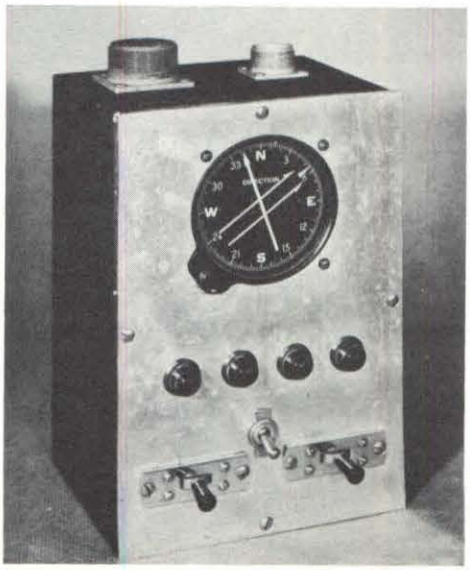
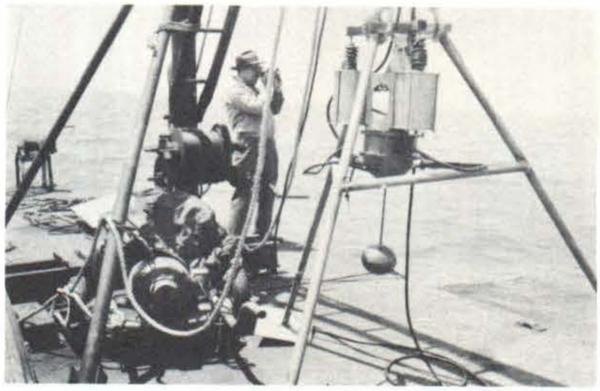
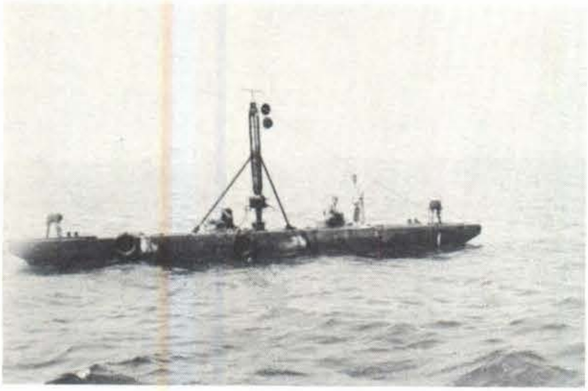


Fig. 21 - Leveling tripod remote control box

Junction Boxes and Oscillograph



Current Meter on Barge Hoist



General View - Test Barge

Current Meter being lowered

Fig. 22 - Current meter and leveling tripod field tests

hence, did not have adequate protection for operation out-of-doors a few feet above the sea.

The experience gained during the operation of this instrument was used to formulate the design criteria for a recording unit more suitable for the particular purpose at hand. This new instrument will be referred to as a Recording Galvanometer rather than as an oscillograph because the latter name implies an instrument for the recording of high speed transient phenomena; whereas, the measurements to be made under this program were of very low frequency. It was decided to design the new galvanometer to use 35 mm microfile film as the recording medium to reduce substantially the bulk of both the records and the instrument itself. Other advantages of using film instead of paper are ease in analysis and in reproduction of duplicate records. The extensive use of the microfile system within the Navy means that records on this film can be processed and studied at most Naval establishments. All types of microfile film are normally used and studied with the help of some type of optical projector which enlarges or magnifies the image. Because of this magnification, it was found possible to operate the film drive at such a speed that a 100-ft spool would be sufficient for a continuous record of three weeks, thus reducing to a minimum the servicing time. One additional criterion was introduced to increase the ease of analysis, i. e., timing marks should be provided on the record.

Description of Instrument

The 35 mm Recording Galvanometer is shown in Fig. 24. Figure 25 is a diagram which will be helpful in identifying the individual elements that can be seen in Fig. 24(b). The galvanometer is 13 in. long, 5 in. wide, 8 5/8 in. high, and weighs 21 pounds. The frame and housing

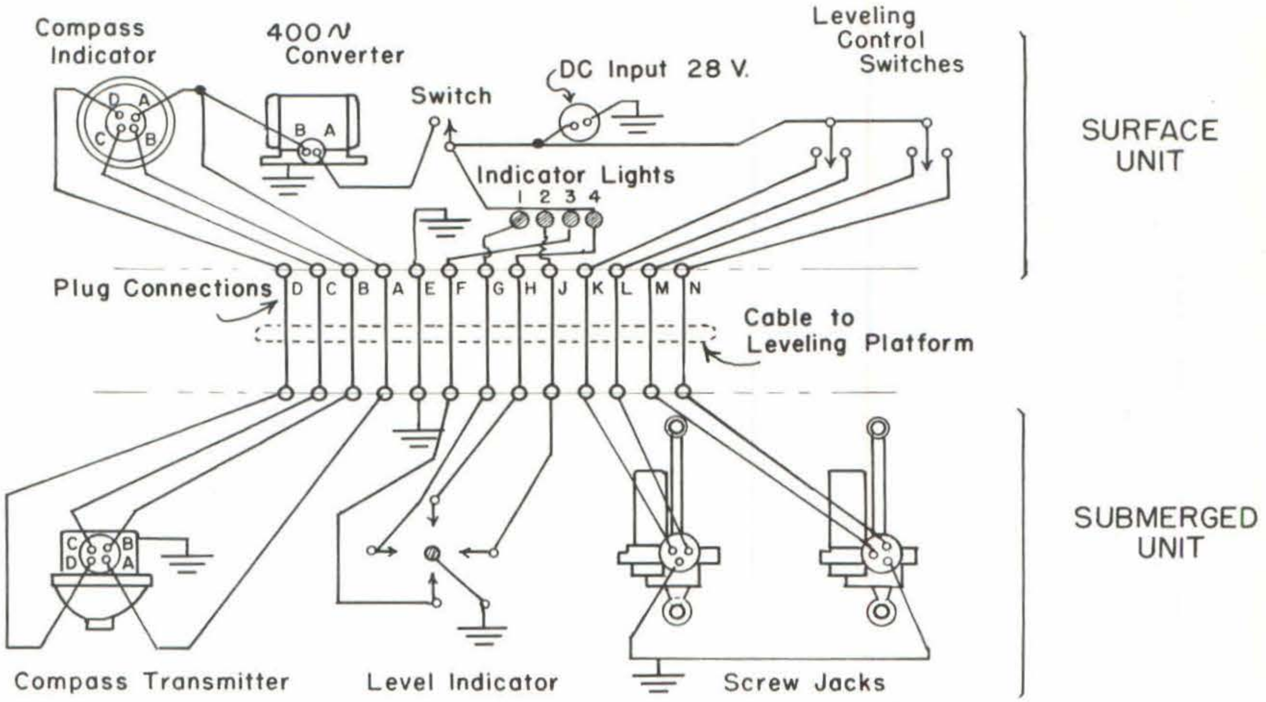


Fig. 23 - Leveling tripod wiring diagram

are fabricated from 24ST dural which is anodized, zinc-chromated and painted to prevent corrosion. All control switches are mounted on the top face of the instrument and a voltmeter is provided to indicate the voltage applied to the galvanometer lamp. The basic units of the galvanometer are the galvanometer block, timing unit, optical system, and film drive.

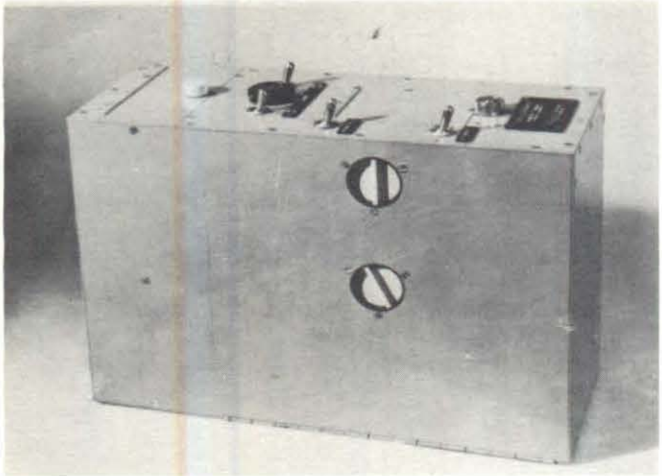
The galvanometer block is a Hathaway model OD-9 and is equipped with nine sensitive galvanometer elements with a natural frequency of 25 cycles per second. The sensitivity of the elements is rated at 7000 mm per milliamp at one meter. The outputs of the indicating instruments are fed into the Recorder through a Cannon plug and are wired to the individual galvanometers through protective fuses. Variations in electrical signals will cause the galvanometers to deflect in proportion to the strength of the impressed electrical currents.

The timing unit causes time marks to be photographed on the film at two-minute intervals. A diagram of this unit is shown in Fig. 25(b). A light source is surrounded by a rotating concentric cylindrical sleeve with six longitudinal light slits at 60 deg. intervals around the periphery. Surrounding the shutter cylinder is a light-tight cylindrical housing with a single longitudinal narrow slit. Alignment of the slits on the stationary and movable sleeves allows light to pass through. The narrow slit of light thus obtained is superimposed on the film by the optical system. One of the slits in the rotary sleeve is 0.008 in. wide and is used to represent hours, and the other slits are 0.005 in. wide and indicate ten-minute periods.

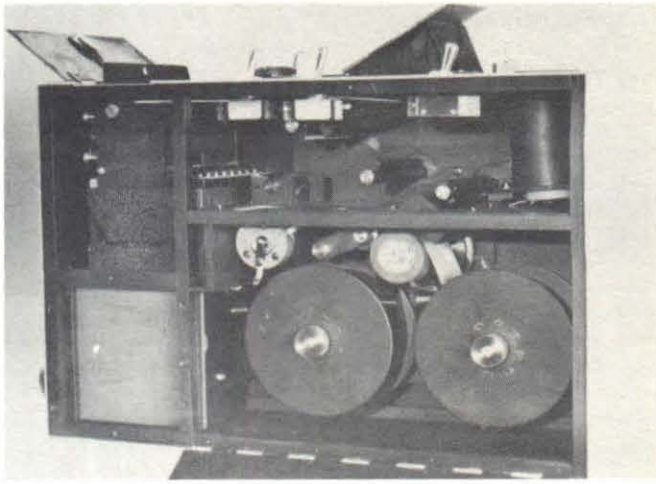
The optical system of the Recorder performs three functions. The galvanometer traces are projected on the film to be photographed. At the same time, a system of mirrors and lenses intercept portions of the light beams from the mirror galvanometers and projects them on a viewing screen. This enables the operator to observe the action of the galvanometer without opening the case and exposing the film. A third optical system projects the timing slit image on the film.

The galvanometer-to-film optical system is as follows: light from a line-source lamp is passed through a lens in front of the galvanometer and strikes the galvanometer mirror. It is then reflected back through the same lens and is deflected by a second mirror through a cylindrical lens and to the film. The focal length of the first lens is such to cause an image of the filament to be formed at the film. The cylindrical condensing lens reduces the line image to a point at the film.

The viewing system has an optical path of the same length and uses the same light source. A mirror intercepts a portion of the light beams from the galvanometers and reflects them to another mirror and cylindrical lens to a ground

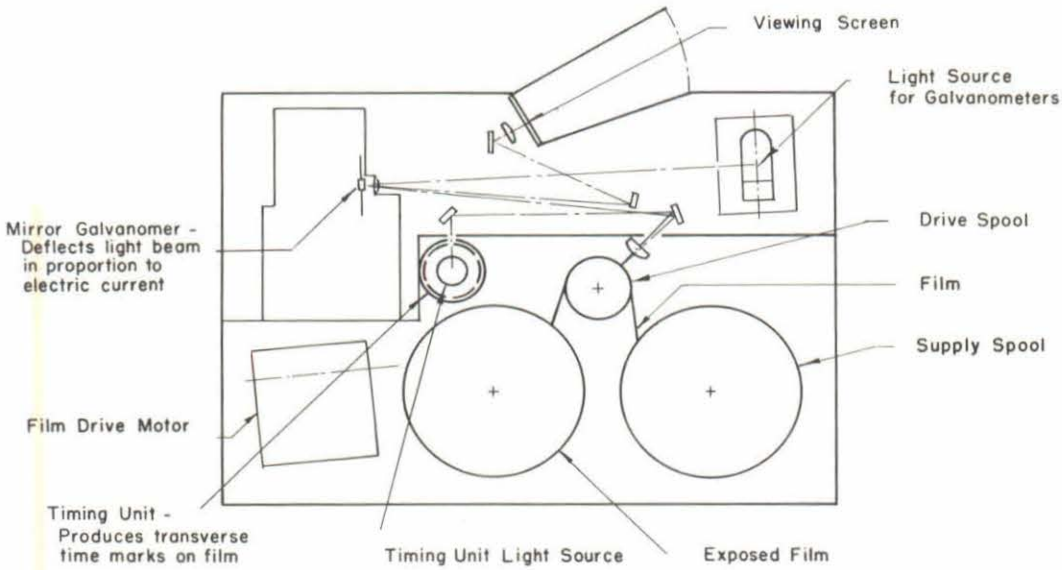


(a) Closed

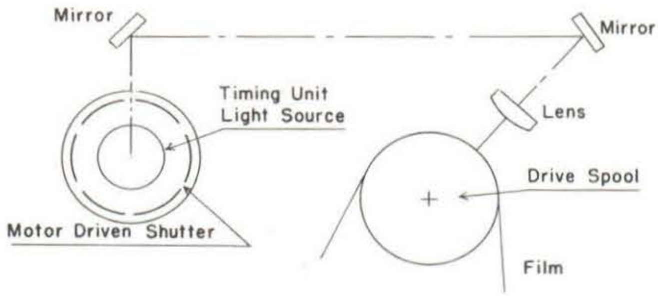


(b) Open

Fig. 24 - 35 mm recording galvanometer



(a) Diagram of internal arrangement



(b) Timing unit of galvanometer

Fig. 25

glass viewing screen. A cloth hood shields the screen from extraneous light for convenience in observation when the access door is opened.

The Recorder is powered by a Bodine KYC 23 synchronous geared motor of 1 rpm output speed. A shaft carrying two worms is coupled to the motor with a rubber coupling. One worm drives the timing unit at 1 rph, and the other the rubber-covered film drive spool. A friction film drive is utilized and a pressure roller idler helps prevent film slippage. Film is supplied by a spool with a constant friction drag, and a geared take-up spool with a slip clutch winds up the exposed film.

The film used is the standard unperforated microfile film and is dye-backed. This allows daylight loading or unloading of the instrument. An overrunning clutch mechanism in the drive spool and an external manual film drive crank allow the film to be advanced by hand.

Operation

To prepare the Recorder for operation, it is connected to a 110 volt, 60 cycle AC power source and the galvanometers are connected to the signals to be recorded. With the recording lamp on the high intensity position and the viewing screen exposed, the galvanometer elements are adjusted until the traces are in convenient positions for recording. Then the recording lamp is shut off, the viewing screen closed, and the film spool access door is opened.

Film is loaded on the supply spool shaft, threaded through the drive spool and to the take-up spool in daylight. Then the access door is closed and the manual film drive crank is rotated five turns. This places the exposed film on the take-up spool and leaves nonexposed film on the drive roller. The machine is now ready for operation. The recording lamp is set to low brilliance and turned on. The drive motor and timing unit are turned on and the instrument is in operation.

F. Radar Current Meter

Purpose

The purpose of this phase of the investigation was the development of the necessary equipment and technique for the measurement by means of radar of both steady and continuous surface currents in the open ocean at ranges up to 10 or 15 miles offshore from the point of measurement.

Development

One of the important questions raised during the model study of the mole for the Naval Base in the Los Angeles Harbor was the cause of the long period surge that occurred from time to time within the harbor area. There was some question as to whether this surge motion was confined within the harbor or whether it was also present in the adjacent open ocean. One of the most well-established and straightforward methods of measuring horizontal water motion of surface currents is the observation of the movement of floats. For such observations to be of value, two requirements must be fulfilled. The motion of the float must be the same as that of the water, and the measurement of the motion of the float must be accurate enough to permit the required degree of sensitivity in determining magnitude and direction of the motion. Practically all of the measurements made in the past have been of steady currents or of very long period oscillatory motion. In fact, about the only oscillatory motion that has been of interest up to the present is that due to tides. For such conditions the required accuracy can be obtained by making observations separated by periods of time measured in hours, or at least in large fractions of hours. Under such conditions, the required accuracy of the measurement of the position of floats is not very great. The most satisfactory measurements have been made by simultaneously tracking the float with two transits, or theodolites, or by determining its position with a relatively long base range-finder. Such methods are usable over ranges of several miles in clear weather during the daytime. An equivalent method is to use a sextant in a boat standing by the float and sighting known objects at the shore.

All of these methods require reasonably large crews and are not well suited to the tracking of several floats spread out over an extended area. None of them is adaptable to automatic tracking and continuous recording of the position. For the purpose at hand, the relatively short period of the surge motion introduced very great difficulties in the use of any of the existing methods. The range of periods of interest was considered to be from one or two minutes to 30 minutes. For low amplitude surges with periods lying at the low end of this range, the total amplitude of the horizontal water motion will be of the order of magnitude of 50 ft. This means that if significant measurements are to be made, consecutive positions of the float must be determined with an accuracy of better than $\pm$ 10 ft. and consecutive readings must be made at intervals of as short as 5 or 10 seconds. None of the existing methods of measurement offered the possibility of meeting these requirements.

The development of radar during the war and its use in the tracking of moving bodies, such as ships, aircraft, and meteorological sounding

Fig. 26 - SCR-584 Radar Set

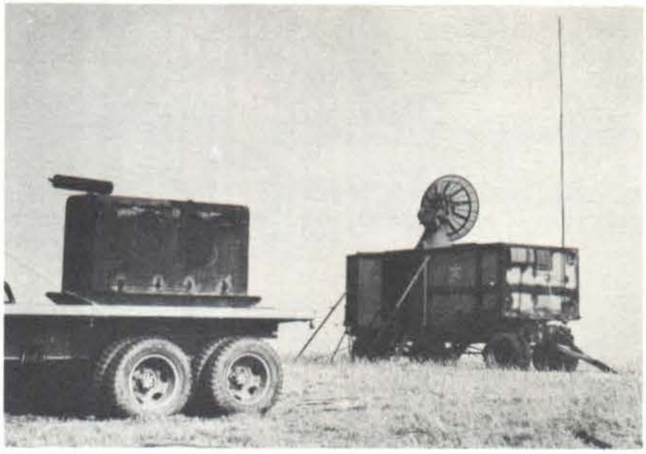


Fig. 27 - Power for radar set supplied by generator mounted on truck

balloons, suggested that similar equipment could be used to good advantage in the tracking of these current floats. The radar method is suitable for day or night work, in thick or clear weather, over distances greatly in excess of that possible by visual methods. It gives both range and azimuth data of sufficient accuracy for most purposes, and it has the great advantage that this data can be constantly and automatically recorded. It was therefore decided to attempt to develop the necessary technique for radar operation, including necessary modification to existing equipment to adapt it for this particular purpose.

The radar set used for this purpose was a mobile army anti-aircraft fire control unit designated as the SCR-584. The unit is housed in a semi-trailer, as shown in Fig. 26. Power for the set is supplied by a gasoline-driven, 15 kw, 3-phase, 110-volt generator mounted on the bed of the truck used to tow the radar trailer. (See Fig. 27). The range of the set is 32,000 yds. on automatic tracking, and it has been used up to 25,000 yds. for the current float tracking. The set operates with a wavelength of 10 cm., which gives the required good resolving power for the use of small reflectors on the floats. The set is designed to have an angular precision of 1 mil and the range can be estimated to about 2 yds. This short wavelength limits the set to uses in which there is a direct line of sight between the transmitter and the target.

The echo of a target appears as a hump or "pip" on the circular sweep of the range oscilloscope. Two range scopes are used, one showing targets from 0 to 32,000 yds., and the other showing targets within a 2,000-yd. band at any selected spot within the 32,000-yd. scale of the other, i.e., the 2,000-yd. scope acts as a vernier for the 32,000-yd. scope. The location of the two range scopes on the operating panel is shown in Fig. 28. A close-up time exposure of the range scopes is shown in Fig. 29. The pips are not actually blurred, as shown in the photograph. The blurring results from the vibration of the trailer during operation. The azimuth of a target, or horizontal angular position of the radar antenna when tracking the target, is read off the dial shown in Fig. 28. The elevation of a target is read off the dial to the left of the azimuth dial, but this can be neglected in current studies. This radar is equipped with a data potentiometer, which gives a voltage proportional to the sine of the azimuth angle. By measuring this voltage, the azimuth angle can be obtained more accurately than with the above-mentioned dial.

A bird's-eye view or plan view of the area commanded by the radar set can be obtained from the PPI, or Plan Position Indicator Oscilloscope. The antenna revolves continuously about a ver-

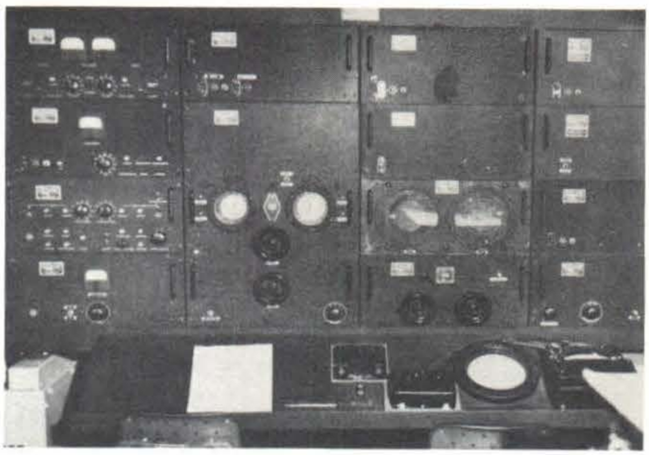


Fig. 28 - Radar control panel showing two range scopes

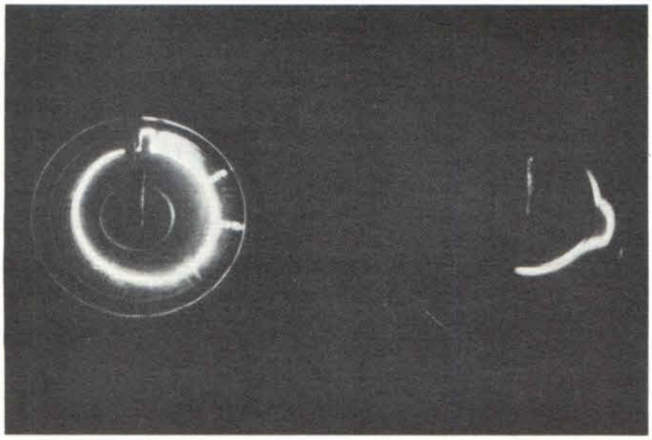


Fig. 29 - Time exposure of range scopes - 32,000 yd and 2,000 yd

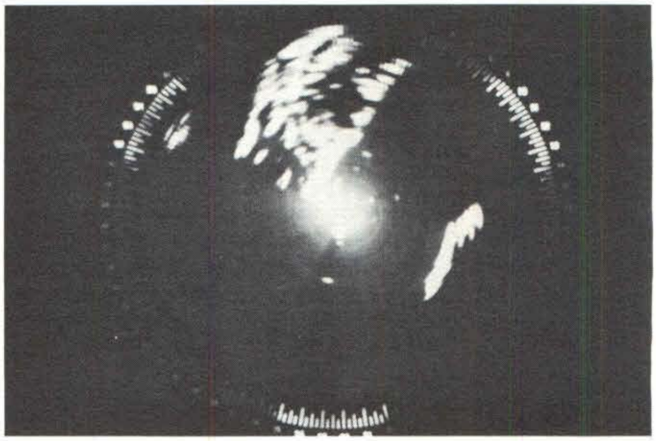


Fig. 30 - PPI Scope - radius 70,000 yds

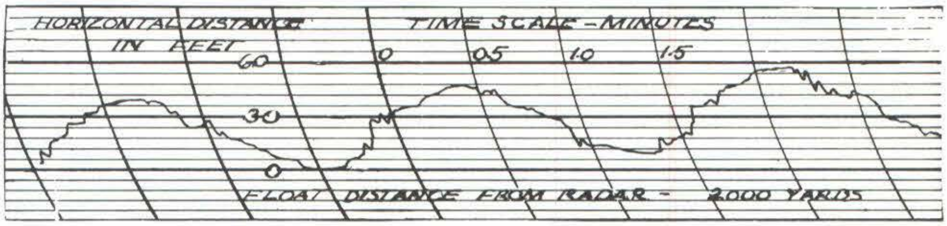
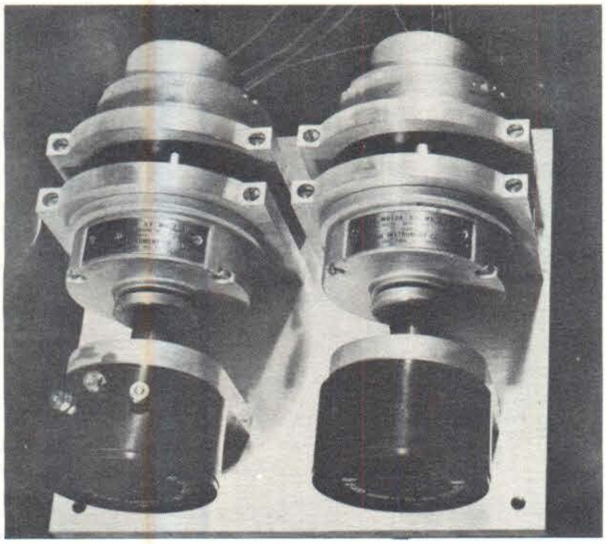


Fig. 31 - Azimuth Test Record - Boat Turning Circle

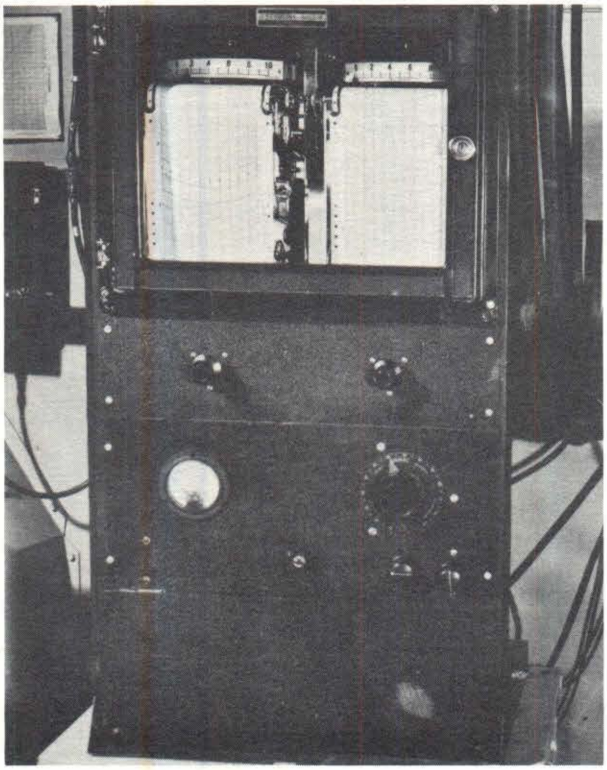
tical axis, and the resulting image on the PPI Scope shows all targets within range in their proper position with respect to the radar set in the center. Fig. 30 is a photograph of the PPI Scope in which the range from the center (position of radar set) to the outer perimeter is 70,000 yds. The PPI Scope cannot be used for accurate determination of the position of objects, but it is used in searching for objects and determining their approximate position.

The SCR-584 radar is equipped for automatic tracking of azimuth, but not for automatic tracking of range. Considerable study showed that it would be rather difficult to adapt this set to make it automatic tracking of range. Therefore, it was decided to develop a recorder system based on the automatic tracking in azimuth and manual tracking in range, but with automatic recording of both azimuth and range. This was done as follows: two selsyns were connected electrically to the radar in such a manner that one of them rotated in synchronism with the azimuth radar, and the other in proportion to the range. These selsyns were used to drive linear instrument potentiometers, which gave a direct current output voltage corresponding to the selsyn position. These signals were fed into a pair of Esterline Angus Recorders, which produced the required records of position vs. time. The instrument type potentiometers had extremely low mechanical friction, which made it possible to maintain a high order of accuracy of recorded measurement. To check the over-all operation of this method, the 38-ft. picket boat used as a service boat in this program was equipped with radar reflector and operated in a tight turning circle. This gave an oscillatory motion quite comparable in magnitude and period to a mild surge having about a 2-minute period. An attempt was made to measure and record this motion with the radar. Figure 31 shows one of these test records, and Fig. 32 the selsyns, potentiometers, and recording instrument panel which were added to the radar to make this automatic recording possible. The test record indicates a very satisfactory performance.

The floats used on the project were designed to be very light and portable so that a launch could be used as a tender and no special handling gear, such as cranes or winches, would be required. The underwater projected area is about 25 times greater than the abovewater area. This resulted from the design requirement that with a wind of 15 knots and a current of 1/4 knot, the water forces would be five times greater than the wind forces, and hence, the wind would not introduce any serious error in the float trajectory. An outline drawing of the float is shown in Fig. 33 in which the main parts are labelled. The float itself is a welded aluminum cylinder 18 in. in diameter and 6 in. high. A two-piece aluminum spar extends below the float. The



(a) Selsyns and Potentiometers



(b) Recording Instrument Panel

Fig. 32 - Equipment added to radar to make automatic recording possible

lower spar telescopes into the upper spar. At the lower end of the upper spar there are attached by hinges three folding aluminum struts spaced equally around the spar; the outer ends of the three struts are stayed to each other with flexible cable. At the bottom of the lower spar is a ballast weight of 25 lbs. Three canvas sails are spread between the extended spar and the system of stayed struts. A mast projects into the air above the float. The radar reflector is mounted at its top. The mast can be made 6 ft., 12 ft., or 18 ft. high. The radar reflector is a so-called "corner reflector" manufactured for use in rubber life rafts. It is constructed of light alloy tubing ribs and a wide mesh screen. The complete float assembly weighs about 50 pounds, of which 25 lbs. is ballast. Fig. 34 is a photograph of the float extended in air to simulate its appearance under water. The horizontal line through the cylindrical float represents the water line. Fig. 35 is an oblique photograph from above in which the three sails and the strut stays can be seen. When the lower spar is telescoped into the upper spar and the struts are folded upward, the sails can be furled and the whole assembly appears as in Fig. 36. This photograph shows the collapsed float ready to be slipped over the side of the launch.

Operation

The floats are launched in a very simple manner. They are collapsed, and a radar "corner" is assembled and mounted on each float. The unit is then slipped over the side at the desired location. When the collapsed float is free in the water, the weight of the ballast pulls the lower spar down out of the upper spar, spreads the struts and the sails and holds the assembly in the position shown previously in Figs. 33 and 34. Figure 37 is a photograph of the float free in the water as seen from the launch. Retrieving of the float is accomplished as follows: the cork float on the pick-up line is seized with a boat hook and brought aboard the launch. The pick-up line is then hauled in, which action turns the float on its side. When the pick-up line has been hauled in until the ballast weights are on the deck rail of the launch, the collapsing line is hauled. This action telescopes the lower spar into the upper spar, the struts fold up, and the sails furl themselves so that the collapsed assembly can be lifted aboard the launch. The pick-up line with its cork float and the collapsing line can be seen clearly in Figs. 33 and 34. Fig. 38 is a photograph of the retrieving operation at the stage where the lower end of the lower spar is on the deck and the operator is hauling in the collapsing line.

The boat used is the 38-ft. picket boat shown in Fig. 39. A boat such as a purse seiner with a broad, low, fantail stern, would be easier to work from and would present less danger of fouling the float in the propeller than the type of boat pictured here. However, six floats have been handled successfully by a crew of two men during average wind and sea conditions. There is a corner reflector mounted on a mast just aft of

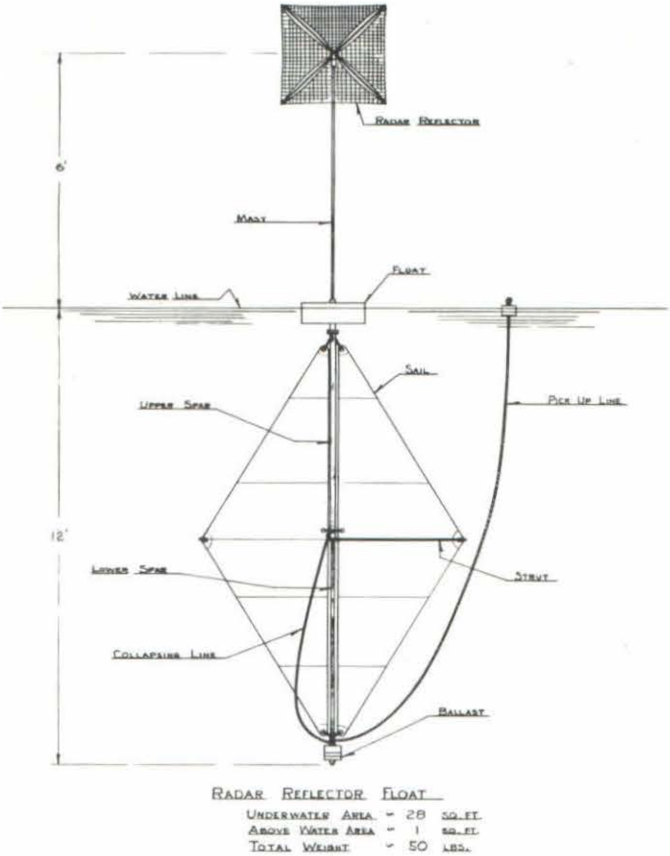


Fig. 33 - Diagram of radar reflector float

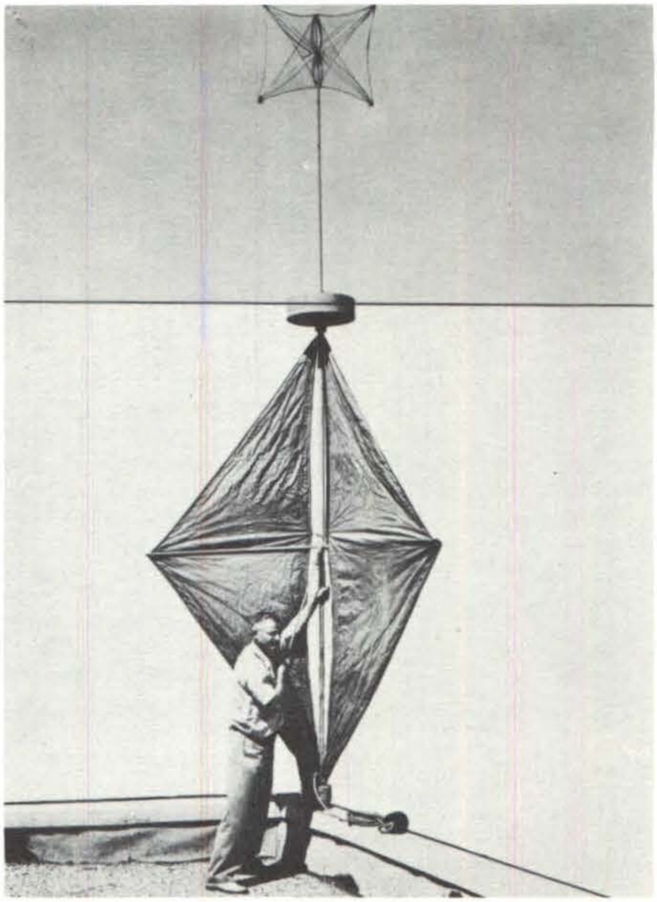


Fig. 34 - Radar reflector float

Fig. 35 - Radar reflector float (oblique view)

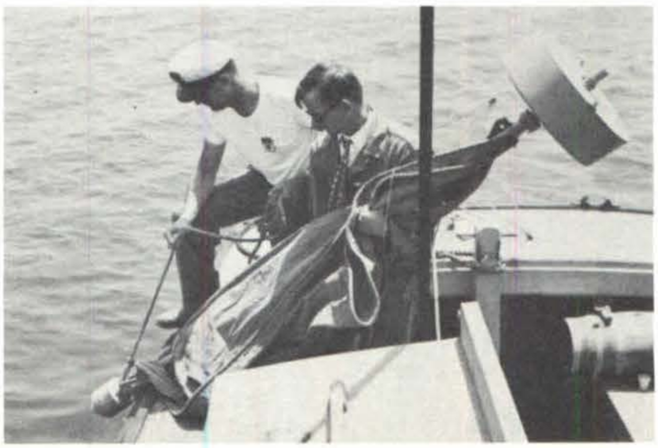


Fig. 36 - Launching the collapsed float

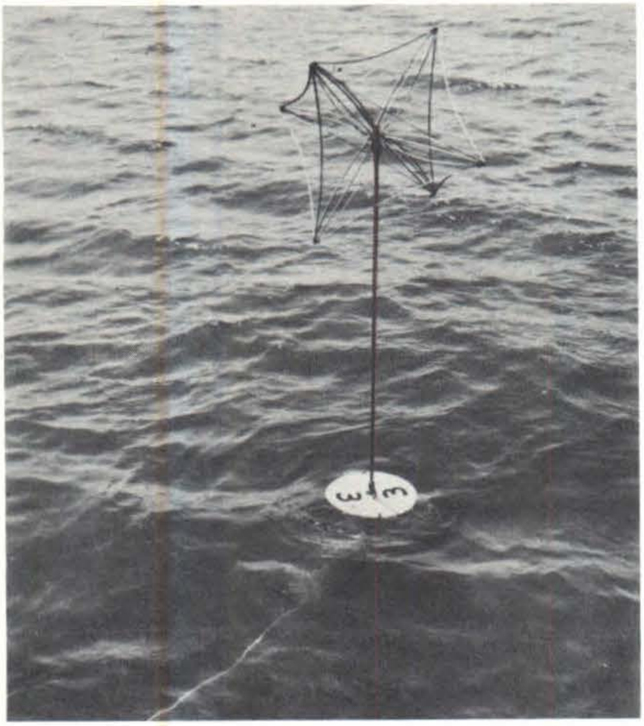


Fig. 37 - Free-drifting reflector float

the pilot house so that the boat is picked up more readily by the radar set. The radio antenna is seen aft. The boat crew is always in contact with the radar crew by means of 25-watt marine radiophones.

This technique has proved to be very suitable for the measurement of steady currents as well as for oscillating ones. For steady currents it is often desirable to use more than one float. A procedure for the tracking of from one to six floats has been developed which requires two radar operators and a crew of two in the attending boat. The boat is directed to the location of the launching of the first float by the radar crew, which is in radiophone communication with the boat, and in addition, can see the boat in the radar scopes. The boat crew launches the float upon receiving word from the radar; and the boat crew then slowly moves away from the float towards the radar about 60 ft. and stands by. The radar crew thus observes that the original pip on the range scope slowly evolves into two pips, separated on the range scale by about 20 yards. This definitely fixes the identity of the float pip; the range, azimuth, and time are recorded, and the position is plotted on the chart. The first float is then temporarily abandoned, and the boat is directed to the location for the launching of Float No. 2, where the same twinning procedure for boat and float pips is accomplished. In this manner all the floats are launched and the initial positions and times are

Fig. 38 - Retrieving the float

recorded. The attending boat proceeds to its base to await notification that the floats are to be retrieved. The radar crew tracks each float in succession at frequent intervals, and records and plots the position and time. Since the floats will not move far during two observations, it is generally easy to find the new position by scanning in the region of the old position. Also, as the number of observations increases and the trajectory of the float becomes clear, the approximate position at the next observation can be predicted from knowledge of the average speed and course of the float. When the period of the test is over, the boat is directed to the floats so that they may be retrieved. The radar set is essential in guiding the boat to the float, since the abovewater part of the float has very little projected area and therefore is difficult to see from the boat.

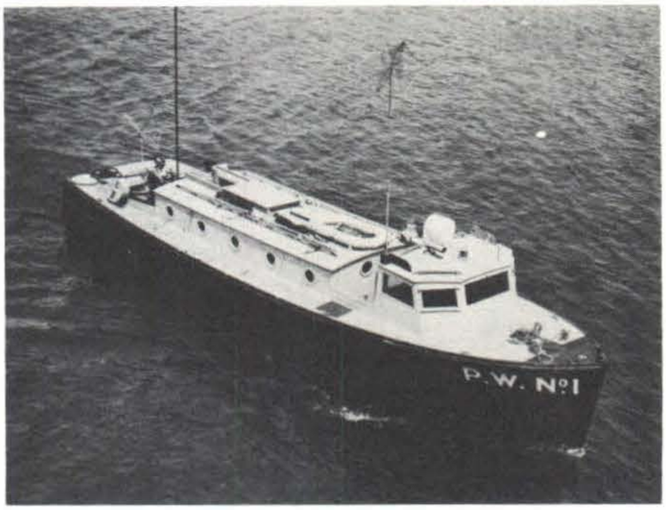


Fig. 39 - The Float Tender - 38-ft picket boat

The maximum working range is governed by the power of the radar and the reflectivity of the radar reflector, assuming that the line-of-sight requirement has been met with respect to the height of the radar location and that the float mast is high compared to the ocean swells. The maximum range for good results has been about 14 mi. on this project, the limiting factor being the reflectivity of the lifeboat-type corner reflectors used. Darkness, fog, and rain have not affected the performance of the radar perceptibly. In such conditions the navigation of the attending boat has been possible by the use of the radar set and the radiotelephones.

The results of a typical current tracking test are shown in Fig. 40. In this test the five floats were released on a line bearing approximately SW from Point Fermin (the location of the radar). The trajectories for the ensuing seven hours are shown on the chart. It must be remembered that the paths shown are not streamlines but are simply trajectories. The currents in this region are composed principally of tidal flows superimposed upon a slow coastal drift, that is, the flow is unsteady and the streamlines are constantly changing. However, the trajectory element between any two observation points can be considered a streamline, since the corresponding time element is very small compared to the period of the current fluctuation. If the streamlines in a selected district are required, the floats are permitted only a short period of free drift, whereupon they are returned to their original starting positions and again released. The resulting trajectory elements can be considered streamline elements; thus, information is secured on the history of the flow streamlines in a small area. In an offshore location, this procedure would result in the usual polar diagram of the rotary tidal currents for the given locality, and in an inshore location the procedure could be used to give an insight into the flow conditions near hydraulic structures of interest.

If the equipment is used for the measurement of short period surge oscillations, only one float is employed, since the radar is called upon to make a continuous record of both azimuth and range. The operation under these conditions is obvious from the previous description.

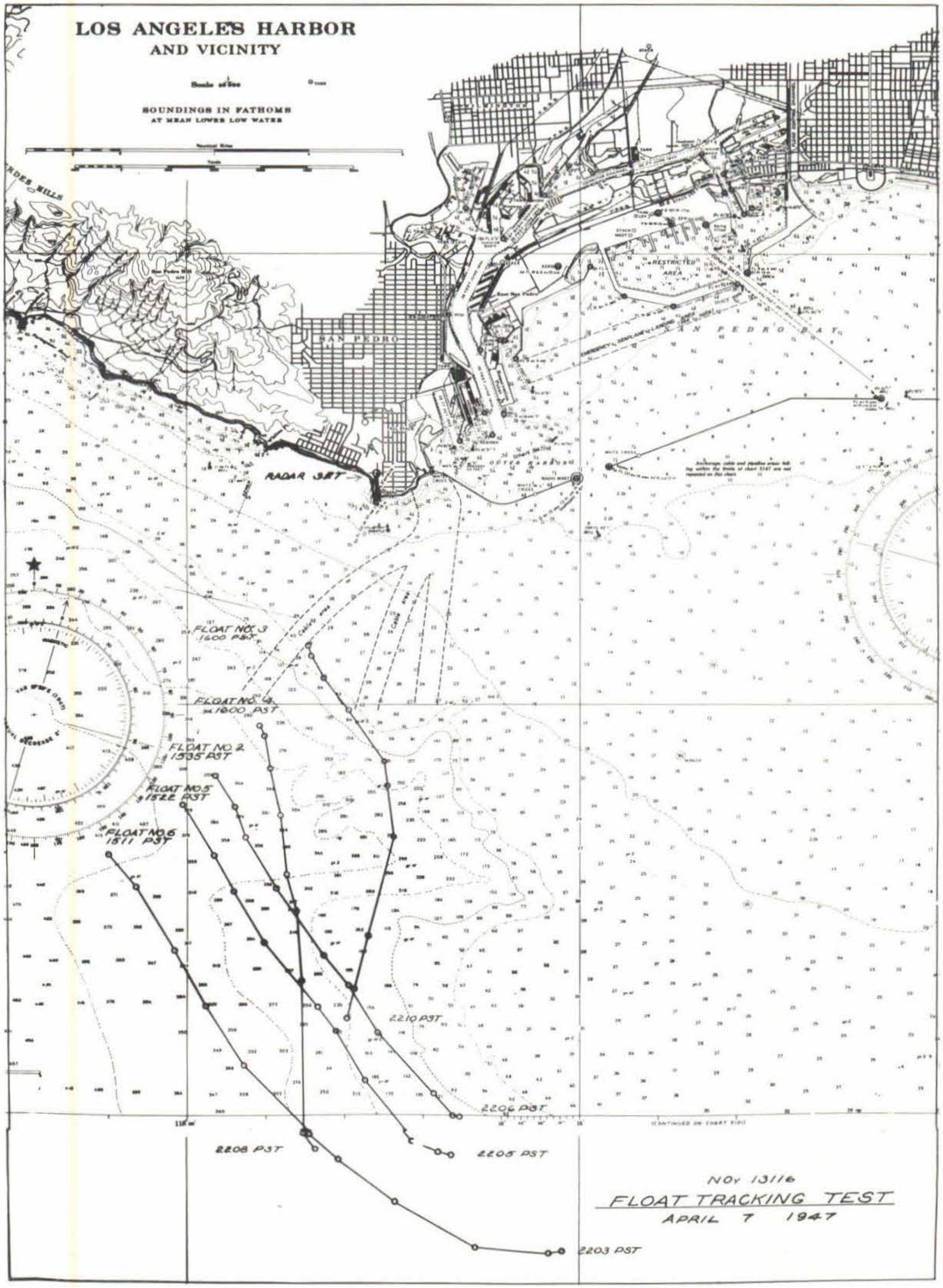


Fig. 40 - Float tracking test

IV.

MEASUREMENTS AND RESULTS

Origin of Los Angeles Harbor Surge

In December 1943 the Hydrodynamics Laboratory of the California Institute of Technology was asked to make a study of the operating characteristics of the proposed mole at Terminal Island Considerable question arose as to the cause of the troublesome surge that occurred from time in the area. A wide range of opinion was advanced by various authorities. At the time, many of them held that the surge was a local phenomenon which was confined to the Los Angeles Harbor area inside of the outer breakwater. The Hydrodynamics Laboratory was of the opinion that the surge was not a local phenomenon, but was present over much of the Southern California coast line. One of the secondary objectives of this present study was to collect additional information concerning this point. The measurements made and information obtained under this contract have shed further light on this subject.

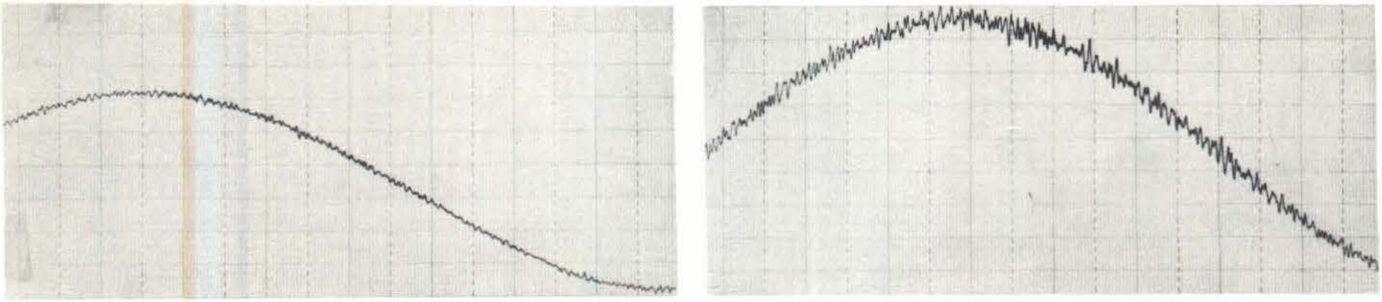
Tide Recorder Data

A Stevens tide recorder was installed at Catalina Island for the basic purpose of obtaining information on the presence of surge outside of the Harbor. The chart ranges, speed, and stilling well were so selected that good records could be obtained of wave motion in which the periods were one minute or longer. This instrument was installed in February 1947, and maintained for the remainder of the three-year duration of the contract. The surge in question, i.e., waves of from one to fifteen minute periods, is a very erratic phenomenon which occurs at very infrequent and unpredictable intervals. Hence, most of the records were quite uninformative. However, in November 1948 a very fortunate coincidence took place. During one of the routine trips in Los Angeles Harbor to Catalina, it was observed that there was a strong lateral water motion, or surge, acting parallel to the pier. The examination of the Stevens wave recorder chart showed that vertical wave motion of an unusual amplitude was being recorded. The period corresponded to that of the lateral water motion, which was observed visually, and was from two to three minutes in length. Records for the same period of time for the tide recorders in Los Angeles Harbor were examined and were found also to indicate the existence of the same type of surge. Tide gage records for this same period were then obtained from the Coast and Geodetic Survey for Port Hueneme, Santa Monica, and San Diego. A two-to-three-minute wave motion of relatively high amplitude was found on these offshore stations during this same time. This furnishes conclusive evidence that a surge phenomenon is not confined to the area inside the breakwater of the Los Angeles Harbor, but it is a general phenomenon of the Southern California Coast. It is interesting to note that during this period of high surge activity, the normal wind waves of approximately 20 second duration, which were observed on the Catalina recorder, were of very small amplitude. Fig. 41 shows two series of records for the Catalina Island, Los Angeles Harbor, San Diego, and Port Hueneme recorders. The first series is for November 22, 1948. This shows a normal condition, with little or no surge. The second series is for November 24 and shows the existence of a greatly increased surge motion for all the stations. This November period of surge was not the only one that was observed during the period of the contract, but it was one of the most pronounced. However, similar correlation between the surges at Catalina and in the Los Angeles Harbor area were observed at other times during the study period.

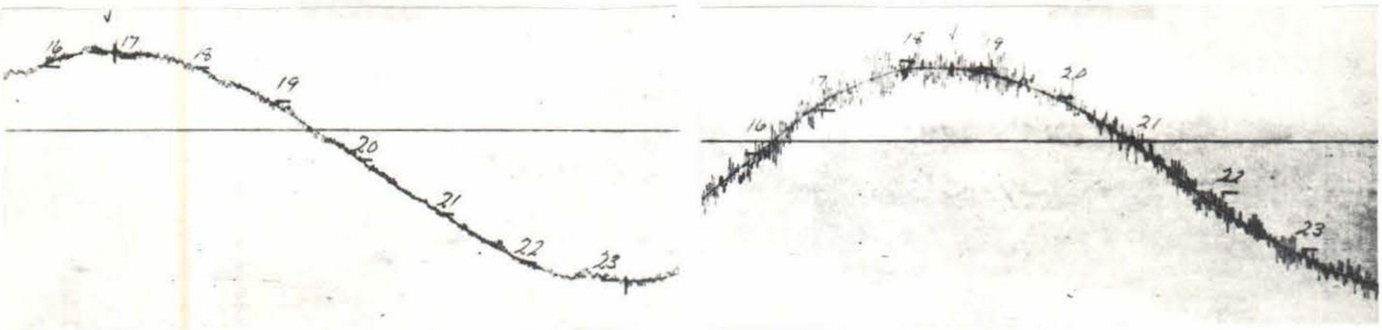
Radar Float Data

Additional independent evidence of the existence of surge outside of the Los Angeles Harbor area was by means of the radar and the float-tracking technique developed under this contract. Although the radar equipment proved to be readily adaptable to the determination of steady currents or of oscillating currents due to changes in tide, it was necessary to push the equipment up towards its maximum sensitivity in order to obtain performance suitable for detecting the existence of horizontal currents oscillating at the relatively short periods of two to three minutes. This was finally accomplished, however, in such a way that the movements of the radar float were recorded automatically, both in azimuth and range. However, the tracking itself was automatic only in azimuth. The range had to be tracked manually. Furthermore, the radar unit required continuous skilled attendance for satisfactory operation. This radar set and float were kept in operation for a period of a few weeks in an attempt to detect surge in the open ocean offshore from the Los Angeles Harbor area.

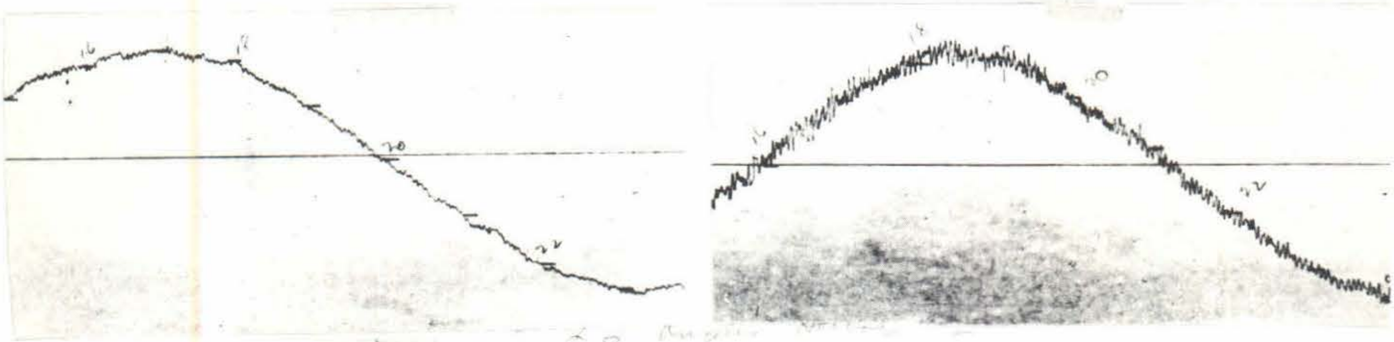
By another fortunate coincidence, a moderate surge set in for a short period during this interval and a measurement of it was obtained from the radar. This second occurrence proved conclusively that the surge is not confined inside the breakwater, but occurs in the open ocean.



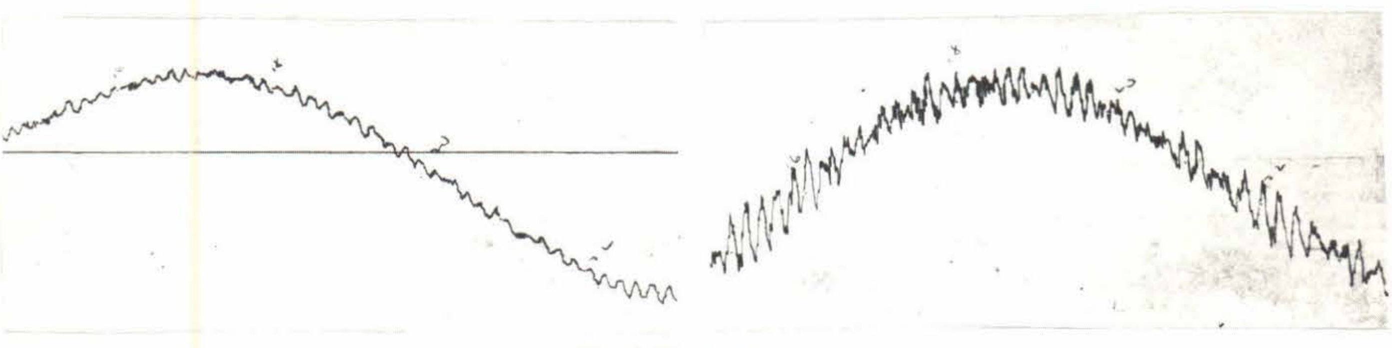
Isthmus, Catalina Island



Los Angeles Harbor



San Diego



Port Hueneme

Series 1
Nov. 22, 1948

Series 2
Nov. 24, 1948

Fig. 41 - Tide Gage Records

There are one or two additional interesting points with regard to the radar measurements. All of the tide recorders were installed on a pier adjacent to a breakwater, or, in other words, very near to the shore. Furthermore, they gave a record only of vertical water motion. In contrast to this, the radar measurements indicated horizontal water motion only and the observations were for an area several miles from the nearest shore.

The over-all conclusions that can be drawn from a consideration of all the measurements on the surge motion obtained under this contract indicate that the surge that is observed in the Los Angeles Harbor is, in effect, a train of long period waves which travel in from the open ocean and strike the shore. There is nothing to indicate that this surge can be thought of as a seiche, i.e., the swinging of the basin which forms the harbor area at its own natural period. The period of the surge in the harbor area is that of the approaching wave train. Differences in amplitude of motion in different localities in the harbor during this same surge are explainable on the basis of resonance between the wave period and the natural period of the local area, i.e., slip or channel or other isolated area, with rather definite boundaries.

Protection Afforded Los Angeles Naval Base by Mole

Another secondary objective of the study made under this contract was to get an additional evaluation of the effectiveness of the mole in protecting the Los Angeles Naval Base.

1. Measurements that are pertinent to this objective are the simultaneous records of the tide recorders inside the mole and in the Los Angeles Harbor area but outside the mole.

2. Other measurements of water motion inside and outside of the mole obtained by the instruments developed under this contract.

3. Measurements of ship motion inside and outside of the mole obtained by the Ship Motion Meter developed under this contract.

Tide Recorder Data

The discussion of the protection afforded by the mole can be considered with reference to three different wave periods:

a. The normal wind wave of from 12 to 20 sec. periods;

b. Surges with periods of from 1 to 3 minutes;

c. Surges of approximately 6 minutes.

The reason for singling out the 6-minute period for individual consideration is that the model study made previously by the California Institute of Technology Hydrodynamics Laboratory of the mole and harbor area, showed that the area inside the mole resonated with an imposed wave train of a 6-minute period. It was concluded from this that high amplitude motion within the mole should be anticipated whenever surge occurred due to wave trains of 6-minute periods. The saving feature of the situation was that previous history had indicated that a surge of 6-min. period had never been known to occur with appreciable amplitude in the Los Angeles Harbor area.

During the entire period of study, the records of the tide recorders within the mole showed only low amplitude wave motion for the normal wind waves in the 12-to-20-sec. period band. During this time several storms occurred during which the amplitude of the waves outside the breakwater, and even within the individual harbor, were relatively high. Thus it can be concluded that the mole furnishes very satisfactory protection against wind waves.

In the case of wave trains with one-to-three-minute periods (surges), the information is much more limited, since such conditions occurred only very rarely. The results are not completely conclusive, particularly because most of the surges that did occur were of relatively low amplitude. However, the indications appear to be that the attenuation of this wave band was at least as great, if not greater than that predicted by the model studies.

Waves Due to Alaskan Earthquake

With reference to the effect of 6-minute surges on the area within the mole, a particularly interesting and puzzling occurrence took place for a few days beginning about April 1, 1946. This corresponds to the time of the Aleutian earthquake which caused the high waves that produced such serious damage at Hawaii. High amplitude wave trains from this same source were recorded along the coast of California and are the subject of this section of the discussion.

The tide recorders in the outer harbor showed one important component that these waves had of a period of approximately six minutes. The waves recorded within the mole showed the same six-minute wave motion, with amplitudes as high or higher than those observed in the outer harbor. This was in direct accordance with the model study; however, no ship damage was recorded during this very active period, and it was difficult to find any ship officers or men who had observed any undue activity of their vessels. This is rather difficult to explain, since the model results had indicated that severe damage was to be expected for these conditions. There are several possible ways of explaining this lack of damage, each of which may be responsible, at least in part, for the low amount of ship motion observed:

a. The occurrence of these high amplitude waves had been predicted, and all vessels had been notified and warned to take adequate precautions. Thus, it is possible that all the ships in the harbor had been secured so adequately that a damaging amount of horizontal motion was impossible.

b. It is difficult to estimate the relationship between period and the potential for causing damage for waves of a given amplitude. For example, when the wave periods are so short that the corresponding wavelength is only a fraction of the ship's length, the waves will cause relatively little motion of the ship. Likewise, if the period is very long, the ship motion will be so gradual that no damage due to the dynamic forces is possible. It was known from experience that two-to-three min. surge could induce damaging ship motion. It was very possible, however, that the six-min. period may be so long as to decrease the damage possibilities.

c. Although the effect of the mole on 6-min. waves may be to produce very little attenuation, or even to increase the amplitude, it will undoubtedly affect the direction of travel of the wave within the mole area. Before the mole was in existence, surges appeared to cause the ships to move in some sort of an elliptical orbit, i.e., the motion, both along the pier and perpendicular to it, was relatively large. The model study indicated that, with the mole in place, the motion due to 6-minute surges would probably be mostly perpendicular to the length of the pier. Such a motion may be easier to control by adequate moorings than the elliptical type of motion. Furthermore, on the basis of calculations of typical cases, it seems probable that the six-minute period is too long to have any appreciable resonant coupling with the natural periods of the ship and mooring line system.

The over-all conclusions that can be drawn from all of the tide records for the various wave bands is that the mole gives as much, if not more, protection to the U. S. Naval Base than was predicted by the model studies. At all times the wave disturbance within the mole area is within the limits of tolerance for the normal use of the area. In other words, the mole has successfully accomplished the purpose for which it was constructed.

Ship Motion Meter Data

Further evidence concerning the amount of protection afforded the area of the Naval Base by the presence of the mole was obtained from the records of the Ship Motion Meter. As soon as the tests on the first unit of the Ship Motion Meter showed that it was capable of giving satisfactory results, it was installed in a semi-permanent fashion on Pier D, which is on the outer leg of the mole. This was a destroyer mooring. An attempt was made to select a destroyer which had been observed to show a more than average motion for this area. The meter was installed under the pier with the actuating line fastened to Destroyer D-558. It was placed in operation on April 13, 1948, and remained until November. During this 6 1/2 month period the maximum amplitude of horizontal motion observed was about 2 ft. The average amplitude was approximately 1 ft. The period of motion varied from 1 1/2 to 5 minutes. At the end of this time the meter was moved because it was felt desirable to install it in some location in which the motion would be greater so as to have a better opportunity to evaluate the over-all performance of the meter. Although the motion of the destroyers in this location was discouragingly low from the standpoint of testing the meter over a wide range of operation, the greatest value of the records is the evidence they present that the motion in this area is consistently very low. This is a quantitative confirmation of the model study. It was predicted on the basis of the model study that the ship motion within the harbor would be greatly reduced, and that the motion in the area adjoining the 30 deg. leg and the East-West leg of the mole would be slightly below the general harbor average.

Ever since the mole was completed, the consensus of those familiar with the condition in the area has been that the mole has afforded very satisfactory protection. The field measurements made at the time of the model study indicated that without the mole, moored ships in this general area could be expected to undergo motions with horizontal amplitudes up to six or eight ft. several times a year, and amplitudes of three or four ft. are relatively common. The present records, therefore, indicate a reduction in amplitude of two-thirds to three-fourths due to the presence of the mole. This measurement can be considered only quantitative in a very rough sense, since there is no way of knowing the relative amplitudes of the imposed waves which caused the ship motions in the two cases.

The Ship Motion Meter was installed next to measure the motion of some floating drydock units. These units were selected because they were believed to have greater amplitudes of motion than those of the destroyers. The floating drydocks were located on Mooring Platform No. 5, which is on the 30 deg. leg of the mole. The meter records showed motions whose amplitudes and periods were very similar to those obtained with Destroyer D-558. The situation again was discouraging from the point of view of testing the range of the meter, but it again confirmed the results of the model study, which had indicated that the two areas should show about the same amount of motion.

The meter was next moved to Berth 58 in the outer harbor. In the two previous locations inside the mole, the vessels, whose motions were being measured, were moored permanently so that continuous records could be taken over long periods of time. Berth 58 is an oil-loading dock. The ships are transient, rarely being moored there for more than a day or two. The motion of three ships was measured in this location:

1. KA-61 (Transport)
2. French Landing Craft (LCT)
3. ARD-19 (Floating Dry Dock)

One of these, the KA-61 Transport, showed a maximum horizontal amplitude of 15 ft. During the interval for which records were taken, the motions of appreciable amplitude had periods which varied from 1 to 3 minutes. The very high amplitudes of motion measured at Berth 58 are particularly impressive because it is quite improbable that they represent the maximum motion which occurs at this location. No attempt was made to select times of maximum activity for the measurements. The meter was simply put into operation whenever any ship was moored adjacent to it. Although Berth 58 always has been known as an area of high activity, the ratio between maximum movements observed here and in the Naval Base area before the mole was installed, was approximately 2:1. When this ratio is compared to the ratio of 7 1/2, or more, to 1 of the Ship Motion Meter measurements, an independent corroboration is obtained of the fact that the mole is giving very satisfactory protection to the area it encloses.

Correlation of Ship Motion and Horizontal Water Motion

Two of the ultimate objectives of the study were the correlation of ship motion with the horizontal water motion, and the evaluation of the permissible amount of ship motion which can occur without interfering with various specific harbor operations, such as loading and unloading, minor repairs, major repairs, etc. No definitive results have been obtained for either of these within the time limits of the project. It must be remembered that such an outcome was partially anticipated at the time that the project was originated, since it was realized that the first step that had to be taken was the development of instruments capable of making the necessary measurements. Indeed, at the time that the study was started, there was no certainty that such instruments could be developed and made to operate successfully within the time available. The situation at the close of the contract period was that instruments, which were capable of making all of the measurements necessary for the obtaining of these ultimate objectives, had been developed, tested, and proved satisfactory. The last stage of the development of the horizontal current meter had just been completed, i.e., the leveling tripod, which made it possible to install the meter at any desired place along the bottom away from local interference due to pier piling, etc.

Additional work was carried on for about a month after the expiration date of the contract, at the contractor's own expense. The objective of this additional work was to get a field test of the meter with its new mounting, and to determine, if possible, the characteristics of the horizontal water motion in one or two arbitrary points in the outer harbor. It was felt that such information would be of considerable interest because there is a complete lack of knowledge concerning the horizontal oscillatory motion of the water except at points immediately adjacent to shoreline structures. The points selected were approximately a mile from shore. Nearly all of the available time was expended in developing a technique for placing and retrieving the meter and tripod from the desired position on the bottom, in ferreting out and eliminating the minor difficulties that always arise when a completely new instrument is put in service, and in developing a satisfactory technique of operation. The final result was that when the end of the additional month arrived, the meter was operating in what was considered to be a quite satisfactory manner, but acceptable records had been obtained for only a relatively few minutes at this given location. This record was much too short to be considered useful in establishing the characteristics of the water motion at that point.

Activities were terminated at this time not only because the contractor did not feel justified in continuing it at his own expense, but also because the technical personnel that had been employed on the project had secured other permanent employment and had to leave to fulfill these obligations.

It is very unfortunate that the work had to be terminated at this time, since all of the major obstacles had apparently been overcome and the way was clear to begin the final step, i.e., the correlation of the ship motion with the water motion that produces it, and the evaluation of permissible motion for various types of activities. It is the writer's opinion that as soon as a reasonable amount of such field data has been collected and evaluated, the harbor designer will be enabled to make two very large steps forward. The first one will be that he can specify in advance the degree of protection which will be required if the harbor is to be used for a given set of purposes. Furthermore, if he has information from the model study of the hydrodynamic characteristics of the harbor, he can design his various developments, taking the best advantage of the varying intensity of the horizontal water motion of the different areas of the harbor. If the harbor is in existence, he can request that measurements be made of the horizontal water motion characteristics in different localities, and on the basis of these measurements, he can predict with surety what the behavior of various types of ships will be in these different locations.

The second step will be made possible by the fact that he will be able to predict the magnitude and type of ship motion at any given location. On the basis of this knowledge, he will be in position to design piers, dolphins, fender pile structures, mooring bitts, etc., to resist without damage the known forces that will act on them. This means that in general he will be able to get some more economical structure with better performance.

It should be emphasized that the type of field studies envisaged to achieve this result will be general, and not local, in character. By this it is meant that the results of measurements made in any one location will be applicable to other locations, i.e., a given amount of horizontal water motion will produce a given amount of ship motion of a specific size and type of ship, independent of the harbor in which it is moored; hence, there is no need to make a series of these measurements in every major harbor. On the other hand, although a comparatively small program of measurements can be expected to yield results for wide application, it must be remembered that there are many variables waiting to be explored. For example, different systems of mooring will apply different constraints to a given ship so that, for the same amount and type of horizontal water motion, the ship may be expected to show quite different excursions in the different directions, depending on the mooring system used. However, many of these questions are of secondary importance as compared to the primary correlation between water and ship motion under simple defined standard conditions.